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Nationwide Evaluation of Combined Sewer Overflows and Urban Stormwater Discharges. Volume I. Executive Summary

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16. ABSTRACT:

A study was conducted by the American Public Works Association and the University of Florida to determine the cost of abating pollution from combined sewer overflows and urban stormwater, the impact of such pollutional discharges on receiving waters, and the pollution potential of such discharges. The study was based upon the availability of existing data and predictive models.

Continuous simulation runs using one year of hourly data were made to determine the statewide level of pollution control with a specific availability of storage volume and treatment rate in five cities: Atlanta, Denver, Minneapolis, San Francisco, and Washington, D.C. This procedure was used to derive generalized equations relating pollution control to storage and treatment. These results were combined into a simple optimization model which determined the optimal mix of storage and treatment for any feasible level of control for any city. Then the nationwide assessment is presented. The results indicate annual costs ranging from $287 million for 35 percent pollution control to $1,039 million for 85 percent pollution control. The corresponding initial capital investment ranges from $1,476 million for 35 percent control to $41,900 million for 85 percent control. These costs can be reduced significantly if stormwater pollution control is integrated with best management practices and integrated into a multi-purpose program.

The balance of the study analyzed existing published and unpublished information to characterize the pollutional potential of urban runoff and to estimate the impact of such runoff on receiving waters. It was found that there appears to be direct correlations between many parameters such as BOD and suspended solids with the amount of street refuse. However, some parameters appear to be related to many site specific factors. As a practical matter it is found necessary to rely on pollution abatement to BOD and suspended solids, even though there are many other pollutants in large concentrations such as heavy metals and phosphorus.

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NATIONWIDE EVALUATION OF COMBINED SEWER OVERFLOWS AND URBAN STORMWATER DISCHARGES

Volume I: Executive Summary

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of this environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This Executive Summary describes the contents of a two volume study which considered the cost of abating pollution resulting from urban stormwater runoff and characterized the quality of urban stormwater runoff and combined sewer overflows in terms of their pollutional strengths.

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ABSTRACT

A study was conducted by the American Public Works Association and the University of Florida to determine: the cost of abating pollution from combined sewer overflows and urban stormwater, the impact of such pollutional discharges on receiving waters, and the pollution potential of such discharges. The study was based upon the availability of existing data and prediction models.

Continuous simulation runs using one year of hourly data were made to determine the attainable level of pollution control with a specified availability of storage volume and treatment rate in five cities: Atlanta, Denver, Minneapolis, San Francisco, and Washington, D.C. This procedure was used to derive generalized equations relating pollution control to storage and treatment. These results were combined into a simple optimization model which determined the optimal mix of storage and treatment for any feasible level of control for any city. Then the nationwide assessment is presented. The results indicate annual costs ranging from $197 million for 35 percent pollution control to $5,032 million for 85 percent pollution control. The corresponding initial capital investment ranges from $3,478 million for 35 percent control to $41,900 million for 85 percent control. These costs can be reduced significantly if stormwater pollution control is integrated with best management practices and integrated into a multi-purpose program.

The balance of the study analyzed existing published and unpublished information to characterize the pollution potential of urban runoff and to estimate the impact of such runoff on receiving waters. It was found that there appears to be direct connections between many parameters such as BOD and suspended solids with the amount of street refuse. However, some parameters appear to be related to more site specific factors. As a practical matter it was found necessary to relate pollution abatement to BOD and suspended solids, even though there are many other pollutants in large concentrations such as heavy metals and phosphorus.

The entire results from this project are contained in the three volumes listed below:

1. American Public Works Association and University of Florida, Nationwide Evaluation of Combined Sewer Overflows and Urban Stormwater Discharges: Volume I, Executive Summary, USEPA Report EPA-600/2-77-064a, 1977.
2. Heaney, J.P., W.C. Huber, M.A. Medina, Jr., M.P. Murphy, S.J. Nix, and S.M. Hasan, Nationwide Evaluation of Combined Sewer Overflows

and Urban Stormwater Discharges: Volume II, Cost Assessment and Impacts, USEPA Report EPA-600/2-77-064[b], 1977.

9. Sullivan, R.H., M.J. Manning, and F.M. Kipp, Nationwide Evaluation of Combined Sewer Overflows and Urban Stormwater Discharges: Volume III, Characterization of Discharges, USEPA Report EPA-600/2-77-064c, 1977.

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Richard Field of USEPA provided invaluable overall guidance and detailed critical review of R/D/E/A throughout the study.

Numerous persons at the University of Florida contributed to this effort under the able direction of James P. Heaney and Wayne C. Huber.

SECTION 1

CONCLUSIONS, RECOMMENDATIONS AND OVERVIEW

CONCLUSIONS

A. Cost Assessment

1. A total of almost 150 million people live in urbanized areas in the United States at an overall average population density of 3.1 persons per acre (12.6 persons per ha). Urbanized areas, as defined, are about 58.5 percent undeveloped. The distribution of the developed land uses is approximately as follows:

Residential	38.4
Industrial	14.8
Commercial	8.6
Other	38.4
Total	100.0

About 14.4 percent of the urban area is served by combined sewers, 39.9 percent by storm sewers, and the balance of the developed area contains unsewered storm drainage. About 33.3 percent of the urban population is served by combined sewer systems, 53.1 percent by storm sewer systems, and the remaining 13.7 percent is unsewered. Average population densities are 16.73 (41.30), 13.00 (32.09), and 4.59 (11.33) persons per acre (persons per ha) in combined, storm and unsewered areas and the overal average developed population density is 9.96 persons per acre (23.6 persons per ha).

2. Annual wet-weather runoff was generated using a runoff coefficient that is a function of imperviousness which in turn is a function of population density. The results indicate an average runoff of 16.5 in.(41.9 cm) per year, 14.0 in. (37.6 cm) per year, and 10.8 in. (27.4 cm) per year from an average precipitation of 35.4 in. (84.8 cm) per year in combined, storm and unsewered urban areas, respectively. Dry-weather flow is a function of population density on the basis of 100 gallons per person-day (379 liters per person-day). The quantities of dry-weather flow in combined, storm, and unsewered areas average 21.8 in. (57.3 cm), 17.5 in. (44.5 cm) and 6.2 in. (15.7 cm) respectively. Average annual dry-weather flow (DWF) is significantly greater than average wet-weather flow (WWF) only in the arid areas. However, in most parts of the country, dry-weather flows represent 30-50 percent of the total (wet plus dry) runoff from urban areas.

5. On the basis of the available data, pollutant loading estimates were developed for wet weather for BOD, suspended solids, volatile solids, total phosphate (PO_4) and total nitrogen (N), and derived as functions of precipitation, land use and population density, the latter only for residential land use. Other land uses are commercial, industrial and open. These estimates indicate that, for the same population density, loads from combined sewered areas are approximately four times higher than those from separate sewered areas. Furthermore, higher population densities in combined sewered areas will increase the ratio even more because loadings are assumed to be an increasing function of population density.

Annual BOD loads were calculated for the 388 urbanized areas for both wet and dry-weather conditions, the latter under the assumption of 0.17 pounds per person-day (0.08 kg per person-day). Annual loads for other parameters may be easily calculated for any urbanized area. The national summary indicates that loading rates for untreated dry-weather flow are higher than for wet-weather flow. However, if 85 percent secondary treatment is assumed for dry-weather BOD generation, wet-weather loads are found to be one third of the total residual loadings in urban areas. Moreover, BOD loadings from combined sewered areas are comparable to loads due to secondary effluents.

4. An evaluation was made of the relative desirability of using a mix of storage with either primary treatment or secondary treatment. The basic trade-off to be evaluated is whether primary treatment is sufficiently less expensive than secondary treatment to offset its lower removal efficiency which necessitates treating a much larger amount of flow to effect an equivalent BOD removal. The results indicate that a primary type of facility is preferable up to BOD removals of about 60 percent. A secondary facility is preferable for higher levels of control.

5. The annual average percent runoff control and the annual number of overflow events were correlated to permit the reader to use either criterion as an effectiveness metric. A precipitation event was assumed to terminate following 12 hours of no precipitation.

6. The final assessment results indicate that, for the entire U.S., total annual costs for 25, 50, 75 and 85 percent BOD control are $397, $985, $2,755, and $5,029 millions of dollars per year. Similarly, the initial capital investment for 25, 50, 75 and 85 percent BOD control is $2,476, $7,301, $22,744, and $61,988 millions of dollars based on 85 percent of the present worth of the total annual cost at an assumed interest rate of 6 percent over 20 years. Note that the incremental costs for wet-weather control increase significantly. This is due to the disproportionately larger control units needed to capture the less frequent, large storms.

7. An analysis was made of the sensitivity of cost allocation among wet-weather quality control and dry-weather quality control (with flow equalization) and wet-weather quantity control (with storage required to reduce runoff rates and volumes). The results suggest that

significant savings from 70 percent at low control levels to 30 percent at high levels might be realized.

8. In addition to using storage-treatment devices to control wet-weather pollution, other management practices are available. A related study suggests that significant savings in control costs could be realized if these other management practices are used in conjunction with storage-treatment. The savings range from about 30 percent at low levels of control to about 10 percent at higher control levels. Further savings could be realized by allocating some of the cost to other purposes, i.e., street sweeping for aesthetics.

9. The relationship between tertiary treatment and wet-weather control was examined by finding the percent wet-weather control to initiate prior to using tertiary treatment. Results indicate that about 5 percent of the wet-weather flow problem should be controlled before initiating tertiary treatment control. BOD removal was used as the effectiveness metric. Different results would be obtained using nutrient control as the criterion.

10. The results of this assessment indicate significantly lower control costs than reported in earlier studies, i.e., the USEPA Needs Survey (initial capital cost = $366.1 x 10^9), and the National Commission on Water Quality (NCWQ) study (initial capital cost of $188.6 x 10^9). The NCWQ study was the only other one which explains its methodology and assumptions. Thus, a comparison with that study has been made. Major differences in results are attributable to the following:
    a. Collection System Costs - The NCWQ estimate includes $85.0 x 10^9 for constructing storm sewers. This study does not view storm sewers as chargeable to pollution control.
    b. Choice of a Design Storm - The NCWQ studies used control of the two year, one hour storm as the basis for their mean estimate of control costs. The concept of a design storm was not used in this study because it was felt that a continuous characterization in terms of percent of the runoff which could be treated was more appropriate since no accepted design event condition exists which also specifies a design antecedent dry-weather period. Analysis indicated that control of the one hour, one month storm would permit capture of 90 percent of the precipitation volume. Rising for the two year, one hour storm yields relatively little incremental control and requires a much higher control volume.

B. Relative Impact of Wet- and Dry-Weather Flows On Receiving Water

1. The relative importance of separate stormwater, combined and dry-weather flow runoff as waste sources generated by the urban environment may be assessed more effectively through the use of models that simulate continuously in time.

f. Based on an overall simulation of waste inputs to the Des Moines River from the Des Moines metropolitan area, various treatment alternatives were investigated. Minimum dissolved oxygen (DO) cumulative frequency curves indicate that:

a. During periods of wet-weather, the urban runoff contribution of BOD is the most significant among all of the urban BOD sources;

b. For existing treatment facilities in Des Moines, Iowa, 62 percent of the wet-weather events were predicted by the mathematical models to violate a 4.0 mg/l minimum DO standard. During these periods of wet weather, the sewage treatment facility provided secondary treatment to municipal wastewater;

c. During periods of dry weather, effluent from the secondary treatment facilities violated the same stream DO standard two percent of all the dry-weather days in 1966;

d. Combining the effects of wet weather and dry weather, the models predicted that DO standard violations would occur 33 total days out of the year;

e. An evaluation of costs incurred indicates that 85 percent BOD control of wet-weather flow, while providing secondary treatment of dry-weather sanitary flow, is an effective treatment strategy. Violations are reduced to 25 days out of the year at an incremental annual cost of approximately $800,000 per year;

f. The benefits received from a reduction of shock loads from urban runoff are not readily quantifiable but should be considered when compared to strategies that involve high levels of municipal wastewater control.

7. Characterization of Combined Sewer Overflows and Urban Stormwater Discharge

a. Urban stormflow can be broadly characterized as: having solids concentrations equal to or greater than raw sewage; BOD concentrations approximately equal to secondary treated wastewater treatment effluent; and bacterial contamination of two to four orders less than untreated domestic wastewater. Combined sewer overflows average less than half the strength of raw domestic sewage, although the volume may produce 100 times the flow of domestic sewage.

b. Runoff quantity and quality are major factors in predicting the need for treatment and type of treatment facilities. Runoff quantity estimating methods have been well developed. The accuracy of physical and hydrologic data are major difficulties. Few areas have sufficient rainfall gauging and other hydrologic monitoring networks.

c. Estimation procedures for runoff quality are not well defined. Two major approaches have been used: characterization of discharge pollution and receiving water monitoring; and identification and evaluation of potential pollutant sources that may contribute to the deterioration of runoff quality. Characterization of discharge pollution suggests construction of treatment facilities whereas source characterization suggests methods of preventing stormflow pollution.

An integrated approach should provide the most cost-effective solution.

4. Only 14 cities were identified where surface runoff quality data in some form were available. Of these, only six related the quality data to physical basin characteristics.

5. Sampling methods and sampling site selection procedures were found to vary widely. Separate storm sewer sampling performed at points in the system where open earthen channels are used appear to add a large solid component due to erosion.

6. Sampling results have been generally expressed in the form of mean pollutant concentrations without regard to rainfall-runoff relationships or variations in time. Thus, the data is not ideally suitable for determining treatment requirements.

7. Soil erosion sediments are perhaps the largest single source of water pollution. Sediments represent pollutional contributions in the form of solids, organic loadings and related oxygen demands, nutrients, acid salts, trace metals, and various other chemicals such as herbicides and pesticides.

8. Sources and temporary storage location(s) of potential pollutants of urban stormflow are often considered as being the same. Rather, streets, rooftops, and catch basins while acting as a temporary point of accumulation should be more accurately considered as an extension of the stormflow collection system.

9. Dust and dirt, generally the fraction of street solids accumulation which will pass a 0.125 in. (0.32 cm) screen, has been used for analysis of the pollutional potential of street surface accumulations. Some investigators have, in addition to sweeping, flushed the street surface and/or vacuumed the surface to obtain a better representation of the solids and soluble material which may be present.

10. A high level of replicability was found for sampling dust and dirt taken at the same site at known time intervals. This, it appears that intensive but not necessarily long sampling periods are needed to characterize pollutional potential of given sites.

11. About 85 percent of the dust and dirt on streets may be associated with wear of the pavement surface. Accumulation loadings on asphaltic surfaced streets have been found to be about 80 percent greater than on concrete surfaces.

12. Public works programs, practices and equipment may be used to affect the quality of urban stormflow. More effective street cleaning programs employing efficient equipment at a relative high frequency of cleaning can remove a major portion of the potential stormflow pollutants. Catch basin cleaning and snow and ice control practices may be additional critical control activities.

13. A direct relationship could not be found between oil pollutants found in receiving waters and potential pollutants found in dust and dirt. Thus, dust and dirt cannot be considered as the sole indicator of receiving water pollution from urban stormflow.

RECOMMENDATIONS

A. Cost Assessment Methodology

1. The methodology developed for this study should be extended to a wider range of situations. The general methodology appears to work well and thus, further use is desirable.

2. Cost and performance data on storage and treatment units should be further refined.

3. The methodology should be extended to account for the interrelationships between storage and treatment especially at higher levels of control where detention times in storage are significant. Associated with this effort could be a study of the impact of different reservoir operating policies. A constant release rate is assumed at present.

4. The frequency equations should be refined to account for snowmelt. An updated relationship between annual overflow events and percent runoff control should be included.

5. Further sensitivity analysis of the cost allocation formulation needs to be made to derive generalized curves for various combinations of influent treatment plant flow equalization and storage available.

6. The tradeoff with tertiary treatment should be evaluated using other pollutants such as nutrients as the effectiveness criterion.

B. Impact Of Urban Water Pollution Control On Receiving Water Quality

1. In order to have basic information on the behavior of receiving waters when subjected to pollutant stresses beyond their natural assimilative capacity, continuous hydrologic models coupled with pollutant transport routines must be applied. It was found throughout this study that large amounts of data were available; however, these data were somewhat less than adequate for modeling purposes. In the area of data requirements some specific recommendations are:
   a. The water quality indicators that will be used for planning purposes should be clearly identified before actual data collection.
   b. The data collection system should be designed to be representative of the receiving water being investigated. Flow velocities, diffusion and dispersion coefficients, tidal cycles, etc., affect the frequency of sampling.
   c. Sampling of receiving waters should be conducted before, during, and after periods of urban runoff.

d. The laboratory procedures utilized should be clearly described. For example, whether natural or artificial (deionized) dilution water was used in performing the standard BOD$_5$ test and the particle size and settling velocity definition of suspended solids.

e. Kinetic constants of biochemical tests (i.e., deoxygenation rates of BOD) should be reported and compared with other locally obtained values.

f. Additional data on nitrification, algal respiration, and benthic demand in water bodies are needed.

g. Characterization of the nitrogenous oxygen demand of waste inputs and the receiving water are needed. The impact of such demands will become more significant since greater numbers of secondary treatment plants are operational.

h. Much more soundness and concentrations of pollutants should be collected and reported.

3. In the realm of modeling efforts, further work is required to characterize: The response of receiving waters to urban runoff and dry weather flow inputs should be characterized after pollutant of waste streams is considered in combination with treatment.

C. Characterization of Combined Sewer Overflows and Urban Stormwater Discharges

1. Research is warranted in the estimation of the contribution of receiving waters through discharges in melt water of the accumulations entrapped in snow and ice resulting directly from source contaminants of the snow, ice and its control methods. Much of the interest exhibited to date in this area has been in terms of chloride contributions as they are liberated from snow and ice control materials. More recently, investigations have provided general characterization data not only for these pollutional contributions, but for source contaminants entrapped within snow and ice deposits as well.

2. Further study and evaluation of the water quality investing characteristics of atmospheric precipitation is warranted. Atmospheric interaction effects as such are little understood, and the contributions of contaminants to surface runoff pollution from these sources may be significant within urban areas. A clearer understanding of these water quality effects would serve to indicate some of the impacts of air pollution heretofore undefined and further pinpoint the necessity for both air pollution and water pollution control. An evaluation of air pollutional contributions to runoff in terms of sanitary engineering water quality parameters alone would prove to be enlightening.

3. An evaluation of the pollutional contributions from the weathering of wear products of street surface and other impervious surface materials should proceed. Indications exist that these materials may represent heretofore undefined sources of runoff contaminants. Determination of the magnitude of pollution involved would prove helpful in establishing effective control strategies for these sources.

4. Urban sediments and erosion products should be evaluated as to their water quality characteristics. The study of erosion products has generally been related to non-urban conditions. Their water quality characteristics are not clearly defined, but should be if the true water quality impacts are to be established.

5. The pollutional contributions attributable to tree and leaf litter should be evaluated in sanitary engineering water quality terms. Vegetative contribution, as such, may represent a significant source of urban runoff water quality impairment during those periods of the year when leaf fall occurs. A clearer understanding of these contributions would be helpful in the assessment of their relative impacts.

6. A further evaluation and assessment of the pollutional potentials of precipitation on other non-street impervious surfaces is warranted. Little real data exists for the assessment of pollutional potentials from these sources.

7. Direct and indirect runoff discharge pollution data is reported on the basis of mean concentration values for the purposes of urban pollutional loading. The time-related effects such as first flush contributions or variations of concentration with flow in time, are not reflected in these average values. In only a few instances, have sufficient discharge information been collected to provide a more complete characterization reflecting these variations.

8. A detailed study of runoff discharges from a completely developed urban drainage basin should be performed. Runoff, as collected by a storm drainage collection system, should be metered and sampled to reflect the time-related responses of the system as to flow and concentration for a variety of rainfall and runoff events. Discreet samples of runoff should be collected and analyzed to provide quality information on these urban runoff flows. The analysis should seek to provide some indications of runoff characterization over time.

9. Standardized data collection and analytical methods should be established for the evaluation of street and non-street impervious surface accumulations and their pollutional potentials for runoff.

10. Sample handling and processing techniques for a subsequent analytical evaluation of the potential physical, chemical and bacteriological water quality characteristics of dry samples should be investigated and standardized. Current practices in the handling of dry samples are varied and often unrelated to the mechanisms by which these potential contaminants become runoff pollution. Thus, further study in this area is warranted.

11. Standard methods and procedures for the metering of runoff flows and for the collection and analysis of urban runoff samples should be developed. Significant efforts in developing standard methods for sampling discharges has been performed to compare alternative sampling

techniques and find desirable standard methods.[9] Proceeding from this work, further methodological development applicable to the specific of urban runoff pollution sampling should be established.

18. Standard procedures should be established for the collection of rainfall-runoff data to be employed in the evaluation of pollutant quantities and control methodologies. These procedures should include methods appropriate for the collection of precipitation data, receiving water quantity monitoring, sample collection, sample processing preparation and sample preservation techniques.

19. A field demonstration effort should be instituted on one or more select small-scale urban drainage sub-basins to achieve a number of significant objectives. Among these would be:

   a. Identification of the pollutional contributions associated with urban sources and computation of coefficients for various measures of street sanitation, maintenance, sweeping, and other controls;

   b. Compilation of sampling and analytical results for both identified potential pollutional contributions - street surface conditions, street sanitation, rainfall, etc. - and for the actual pollutional loadings related to these potential pollutional contributions;

   c. Evaluation of the effectiveness of local control methods applicable to the prevention of runoff contamination;

   d. Comparison of both potential and actual pollutional contributions among existing types of development in various land uses;

   e. Assessment of the impacts of the first flush phenomenon, including the contributions of catch basins and sewer system accumulations.

14. The accumulation and removal mechanisms available to the deposition of pollutants on street surfaces and other impervious surfaces should be evaluated. These would include: airborne, water-borne, vehicular-produced, and miscellaneous depositions, as well as wind erosion, run-off, transportation-related and intentional removals. These accumulation and removal mechanisms should be evaluated in terms of various street configurations, paving types, curb and other barrier heights, land use and other variables.

15. The removal of street surface contaminants by runoff flows should be further investigated to establish the physical processes involved. Such evaluation should consider the hydraulic modeling of rainfall and runoff on representative street sections if necessary.

[9] Weichinger, Richard R., et al., "Recommended Methodology for the Study of Urban Storm Generated Pollution and Control," USEPA Report No. EPA-670/2-76-145, Envirex, Inc., August, 1976.

16. The evaluation of the effectiveness of street cleaning equipment for pollution control technology in reducing the levels of potential pollutants on street surfaces should be continued. Such studies should relate air and water pollution.

17. The conservation contributions of urban erosion sediments should be further investigated in relationship with the major variables involved--soil characteristics, cover management practices, rainfall and other hydrologic conditions, physical configurations and other measurable parameters. Although annual estimating methods exist for agricultural sediment production, shorter-term single rainfall erosion responses remain to be determined or the applicability of existing estimating methods to urban areas and individual rainfall occurrences should be validated.

18. Sources of potential pollution for urban runoff should be evaluated to provide a basis of predicting in connection with existing analytical methodologies or new assessment methodologies should be developed. Little real information in this regard is available.

19. Further study and evaluation of recalibration techniques employing verification data for the calibration of existing models and their use for the prediction of pollutional contributions due to subsequent runoff events should be undertaken. Recalibration techniques employing discharge information have been shown to be promising approaches for fine tuning models to secure higher levels of accuracy in prediction. These procedures should be further evaluated and more highly developed for existing models where they may apply.

20. Further research into urban development characteristics should be instituted, and recommended procedures for the collection of this data should be established.

21. Various urban development parameters should be studied and analyzed as to their applicability as meaningful parameters for the estimation of urban runoff pollution. This analysis should proceed on the basis of real runoff quality discharge information. The relative importance of various urban development parameters with respect to runoff discharge pollutional characteristics should be established.

22. Further research to establish on a nationwide basis, the contribution of the pollutional contributions in receiving waters is appropriate. These may be proposed on generalized per acre annual collection for various types of land use.

23. The effects of benthal deposits and other sources of pollutional impacts on receiving water should be further studied and evaluated. The impact of these sources on water quality is generally significant and of considerable interest. The fate of heavy metals is of particular concern.

OVERVIEW

The American Public Works Association (APWA) and the University of Florida (UF) conducted a study to characterize urban stormflow and combined sewer overflows and to determine the cost of control or treatment of receiving water pollution from such sources. The study encompassed a number of objectives which included: the generalization of the quantity and quality characterization of urban stormflow and combined sewer overflows; an assessment of the pollutional significance of these wastewater flows on a national basis as to their impacts; applicable prevention, abatement and control methods and control costs; and a critical evaluation of the data which was available.

The study was designed to utilize existing published and unpublished sources of information and data.

Some broad inconsistencies exist within the body of information uncovered as to the handling and reporting of various aspects of the complex physical processes involved, sampling methods and equipment, the pollutants measured, and the results identified. While the diversity and variation encountered is representative of the current state of the art, it also reflects the evolutionary character of this area of study over the past ten years or so. Nevertheless, the information uncovered is representative of the best available for the purposes of this project.

Highlights of the two volumes of the study report are included in this third volume, Executive Summary. Section II describes the overall cost assessment results and methodology used. Section III evaluates the impact of urban stormflow and combined sewer overflows on receiving water quality. Section IV describes the essential features of the characterization portion of the study.

SECTION II

COST ASSESSMENT

During the past decade, much effort has been expended in identifying and analyzing the wet-weather pollution control problem. The initial concern with combined sewer overflows expanded to consideration of stormwater runoff in general. This study assesses the costs of controlling wet-weather pollution to varying degrees. A key question is what is the relative importance of various sources of wet-weather pollution and how does wet-weather pollution control compare to dry-weather pollution control? Also, what is its impact on receiving water?

Control of wet-weather pollution is distinctly different than the traditional dry-weather problem. In wet-weather pollution control, one would normally use a mix of storage and treatment, not treatment alone. Thus new techniques are needed to determine optimal mixes of storage and treatment. Numerous effectiveness criteria for wet-weather control have been used, e.g., number of overflows, percent runoff control, percent BOD control. For wet-weather control, the most critical impact on the receiving water does not necessarily occur under low flow conditions. How should the critical conditions be defined? Basic questions of this nature arose throughout the study because it is such a relatively new area of concern. Thus the final estimate could vary widely if some of these assumptions are changed. However, the approach is a fairly general one and assumptions are stated explicitly. Thus, the interested reader can refine the estimates as better information becomes available. The remainder of this section summarizes the cost assessment.

DEMOGRAPHIC CHARACTERISTICS OF THE URBANIZED AREAS

Urban areas in this study have been taken as the 248 urbanized areas defined by the Bureau of the Census of the US Department of Commerce in the 1970 census, and other urban areas. The 248 urbanized areas defined in 1970 are generally characterized as having: (1)

- a central city or urban core of 50,000 or more inhabitants;
- closely inhabited surroundings, consisting of incorporated places of 100 housing units or more; and small unincorporated parcels with population densities of 1,000 inhabitants per sq mi (386 per sq km) or more; and

- other small unincorporated areas that may eliminate enclaves, square up the geometry of the urbanized area or provide a linkage to other enumeration districts fulfilling the overall criteria within 1.5 mi (2.5 km) of the main body of the urbanized area.

All 348 urbanized areas in the United States were analyzed in varying levels of detail. Population density distribution functions were developed for 50 urbanized areas. These results were extrapolated to the other 298 urbanized areas. Land use information was derived based on a statistical analysis of 106 cities. (2) The results for all USEPA regions and the entire U.S. are shown in Table 1. A total of almost 150 million people live in urbanized areas in the United States at an overall average population density of 5.1 persons per acre (12.6 persons per ha). Urbanized areas, as defined, are about 46.2 percent undeveloped as estimated in Table 2. The distribution of the developed land uses is approximately as follows:

Residential	38.4
Industrial	14.8
Commercial	8.6
Other	38.2
Total	100.0

Information was obtained on population and area served by combined sewerage systems. The population and area served by storm sewers and in the unsewered area were estimated as residuals. All areas with a developed population density of less than 5 persons per acre (12 persons per ha) were assumed to be unsewered. The results, shown in Table 3, indicate that about 14.4 percent of the urban area is served by combined sewers, 38.3 percent by storm sewers, and the balance of the developed area is unsewered. Table 4 indicates that 25.2 percent of urban population is served by combined sewer systems, 52.1 percent by storm sewer systems, and the remaining 22.7 percent is unsewered. Table 5 indicates nationwide average developed population densities of 16.73 (41.30), 13.00 (32.09), and 4.59 (11.33) persons per acre (persons per ha) in combined, storm and unsewered areas and an overall average developed population density of 9.56 persons per acre (23.6 persons per ha).

RUNOFF ANALYSIS

Stormwater Flow Prediction

Techniques for prediction of runoff quantities vary from very simple methods of the Rational Method type to sophisticated models of the nature of SWMM. The Storage, Treatment, Overflow and Runoff Model (STORM) was developed by Water Resources Engineers, Inc.(WRE) for the Hydrologic Engineering Center (HEC) of the Corps of Engineers. (3) The model was designed for planning purposes, i.e., for long-term simulation of many storm events using an hourly time step. Techniques used in STORM are relatively simple, relying on weighted average runoff coefficients and a simple loss function to predict

TABLE 1. DEMOGRAPHIC CHARACTERISTICS OF THE URBAN AREAS

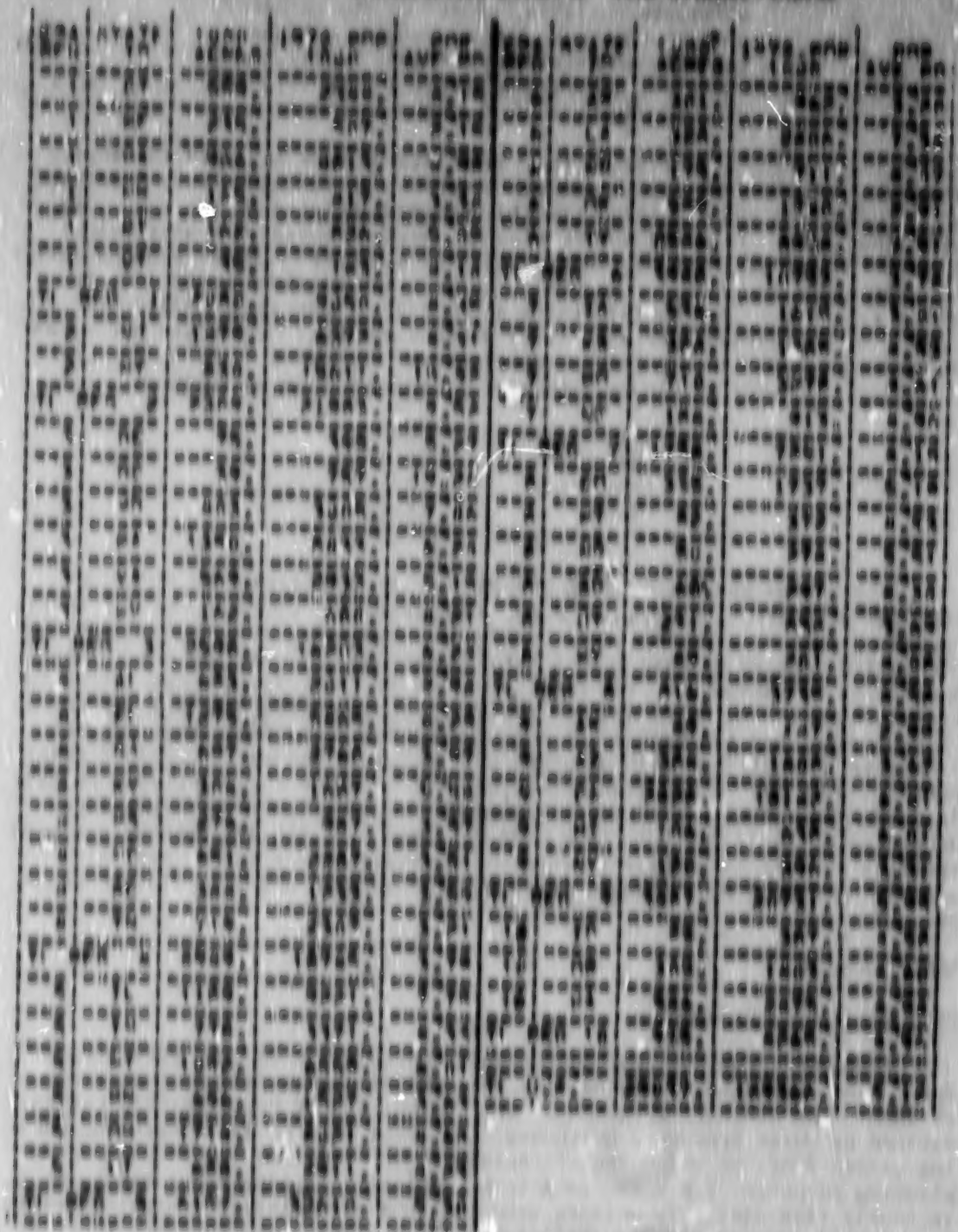

TABLE 3. LAND USE DISTRIBUTION FOR THE URBAN AREAS IN THE U.S.

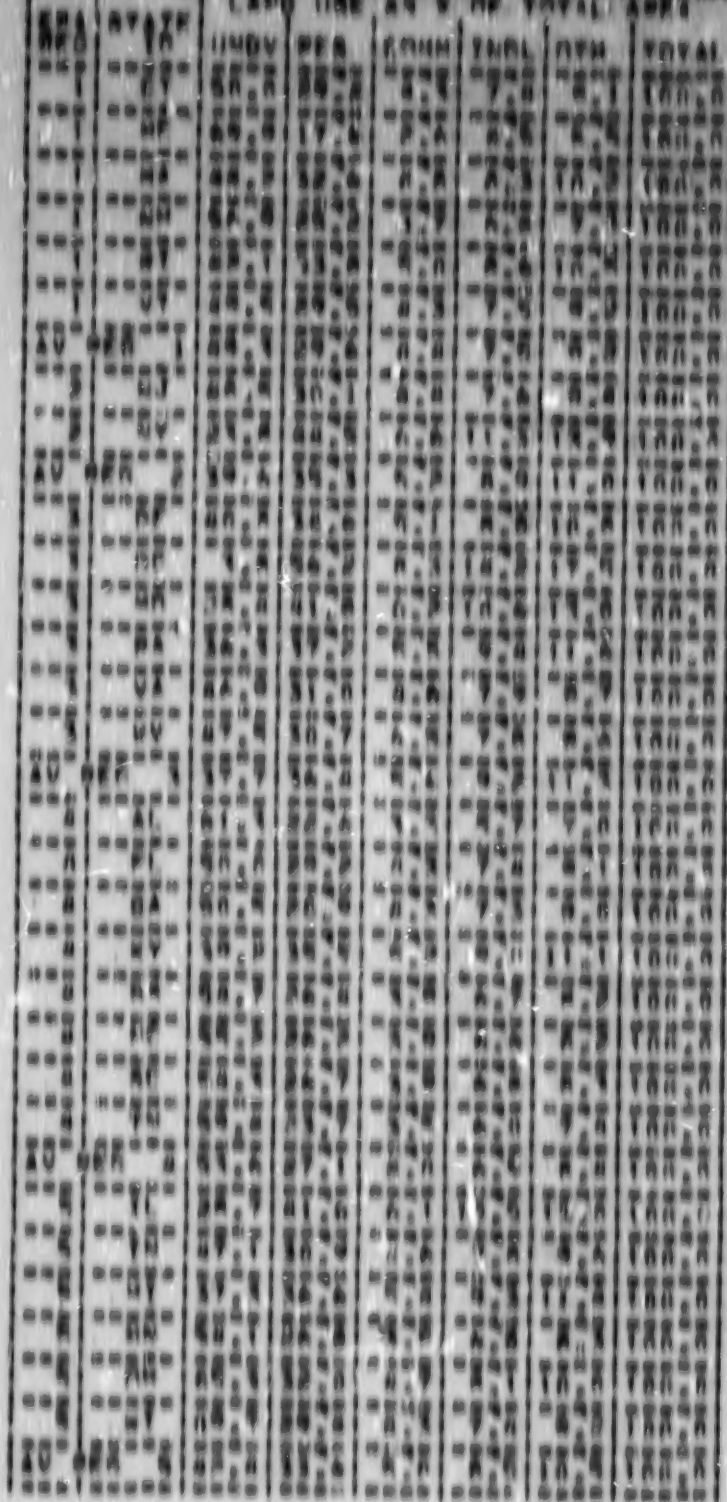

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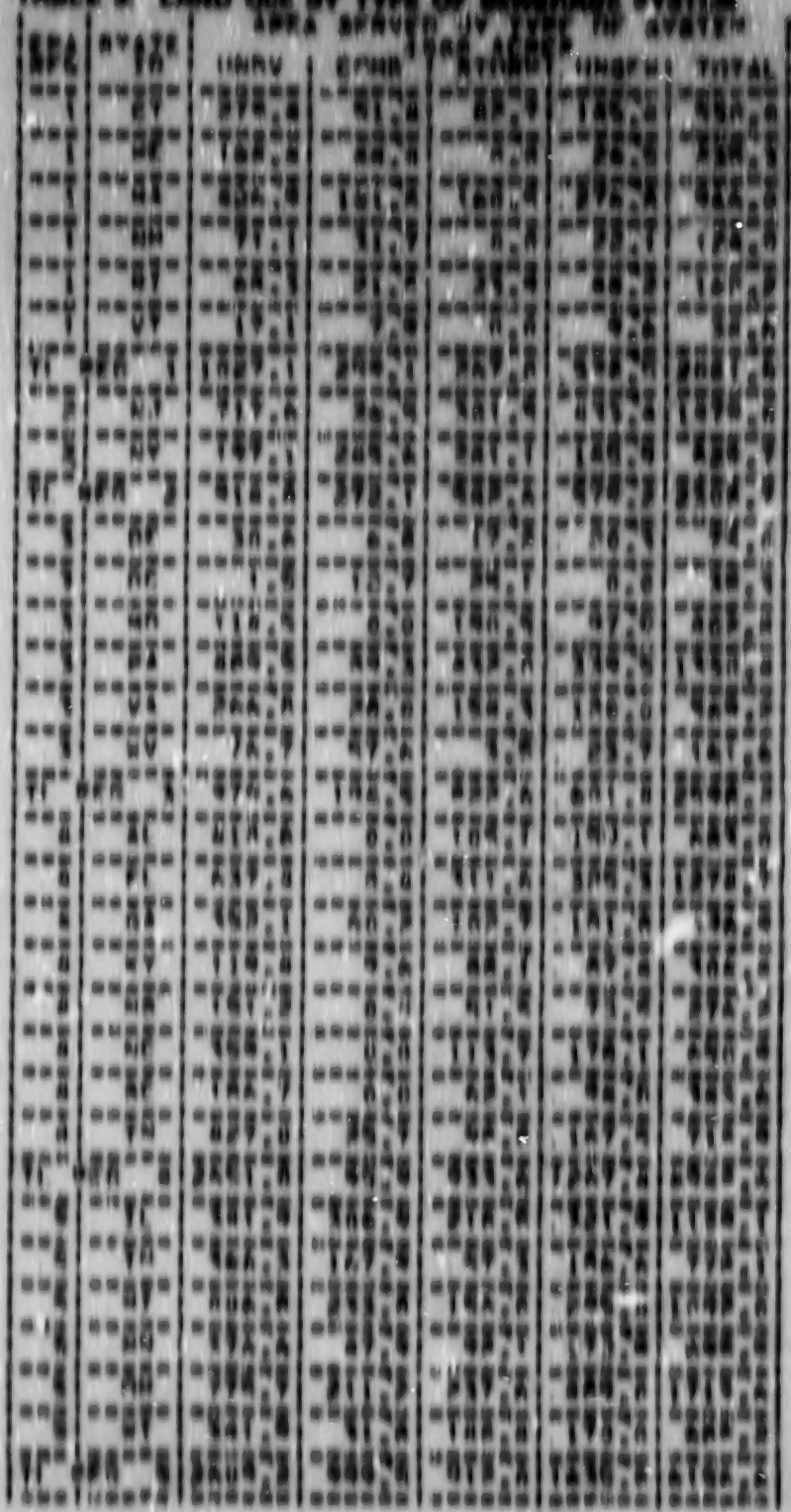
TABLE 7 (cont'd)

EPA	STATE	LAND USE AS % OF TOTAL AREA					
		URBAN	RES.	COMM.	IND.	OTH.	TOTAL
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 3. LAND USE BY TYPE OF SEWERAGE SYSTEM



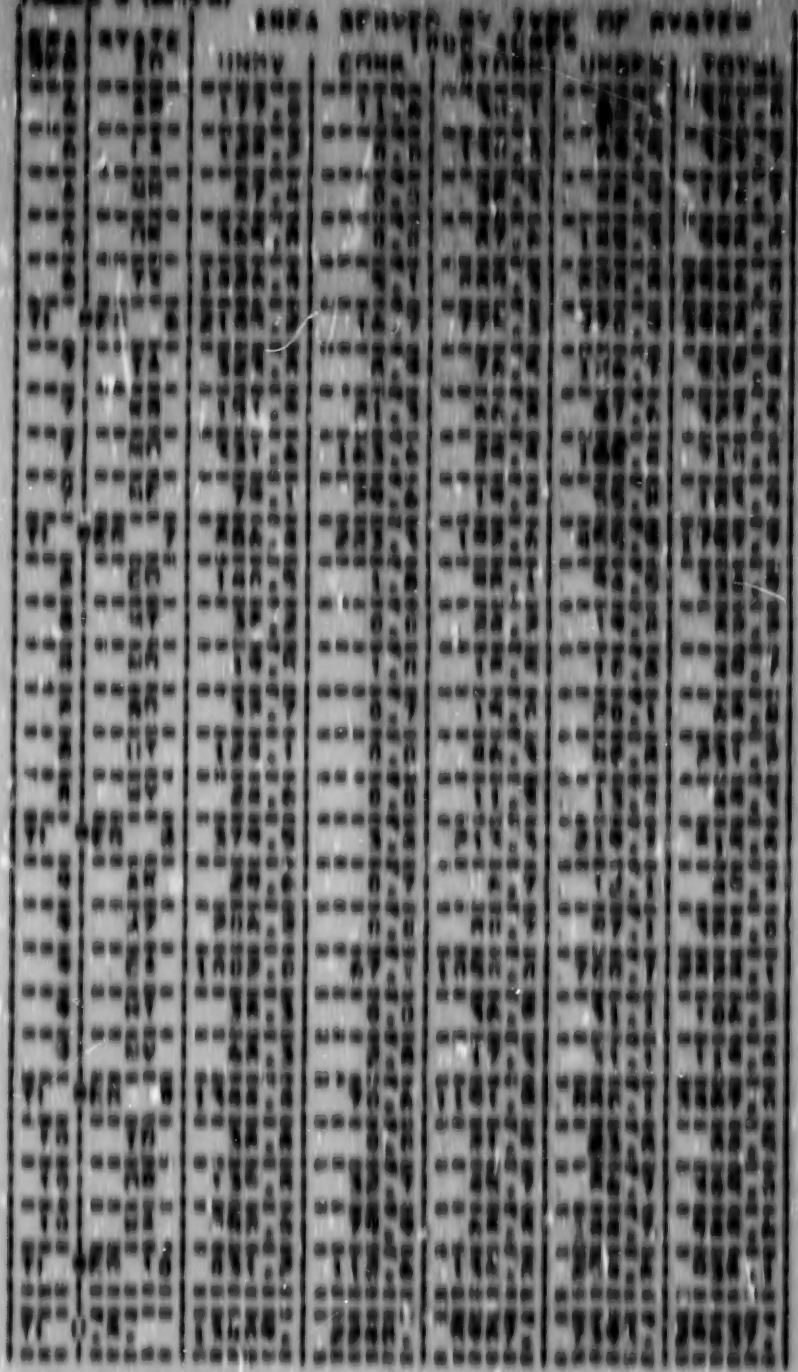


TABLE 4. POPULATION BY TYPE OF SEWERAGE SYSTEM

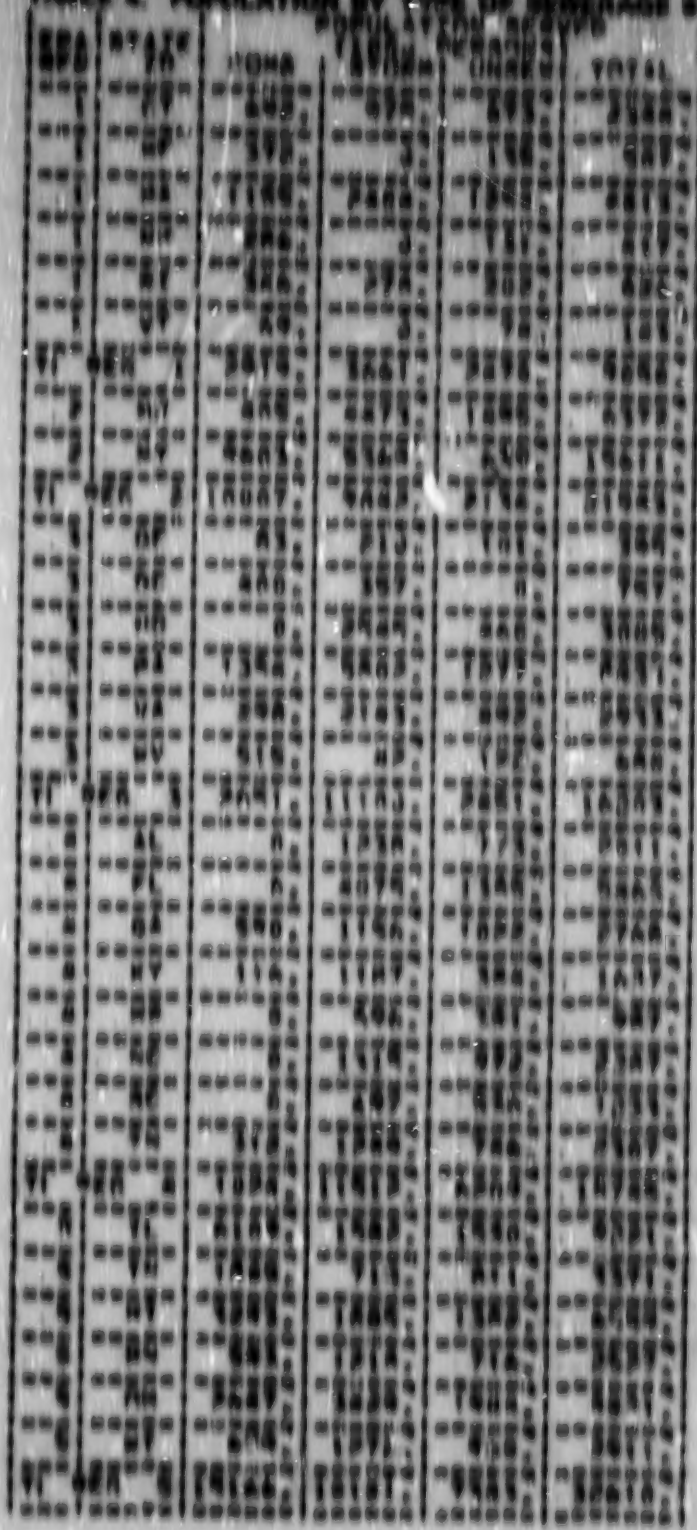


TABLE 4 (cont'd)

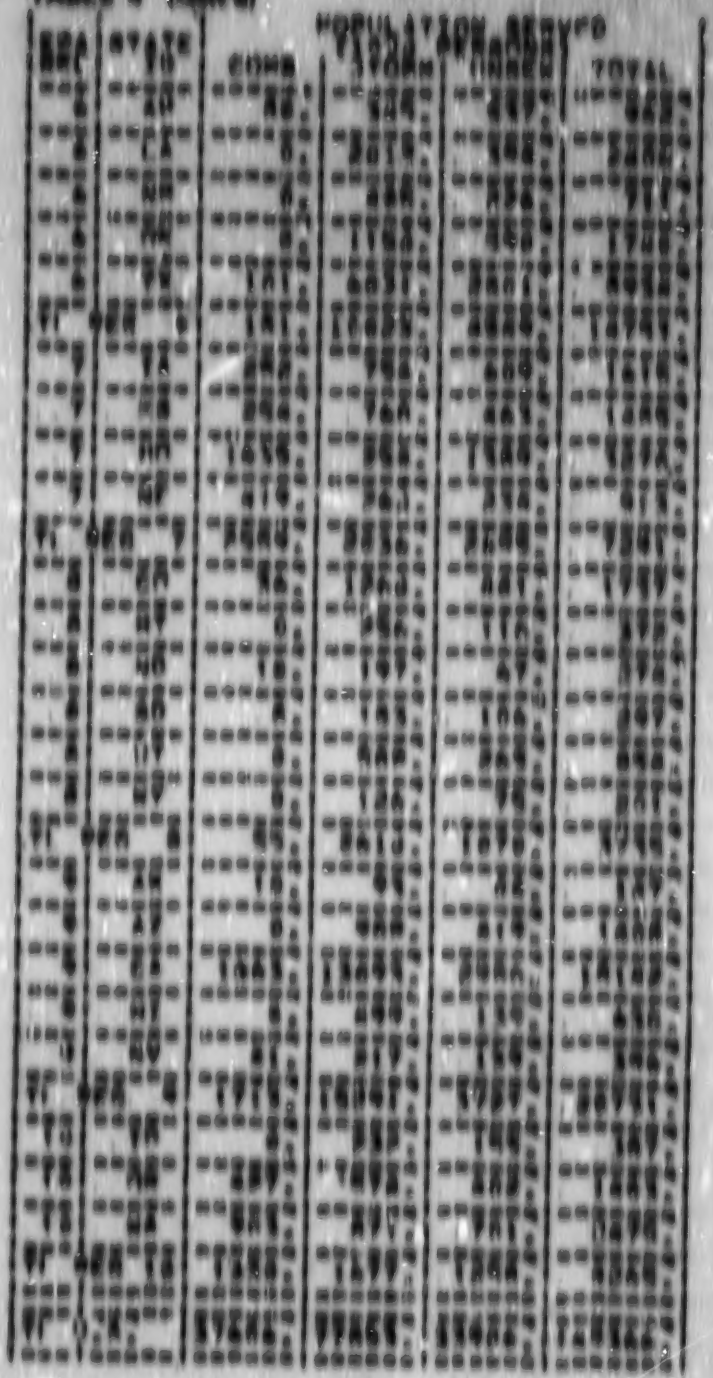
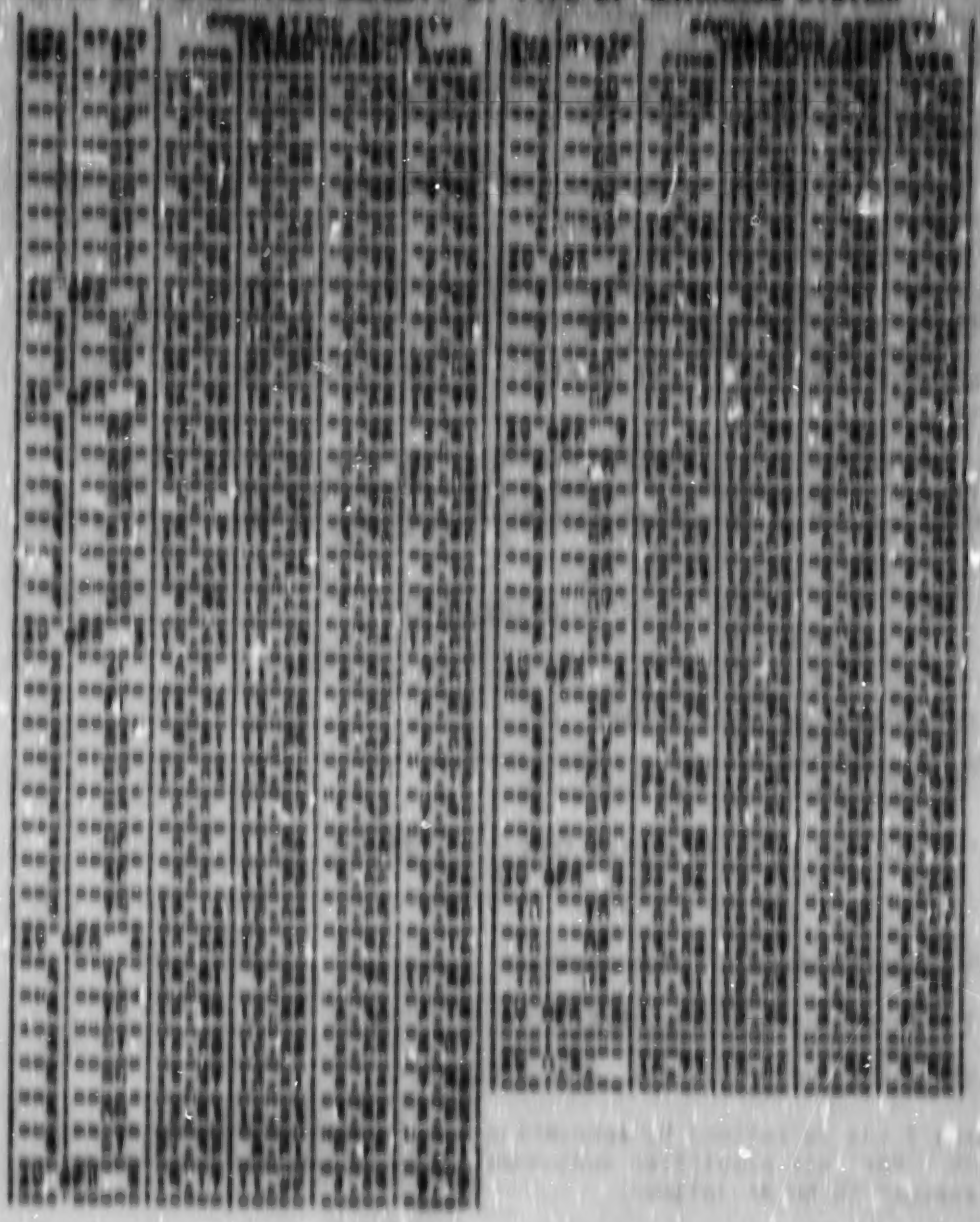


TABLE 5. POPULATION DENSITY BY TYPE OF SEWERAGE SYSTEM



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hourly runoff volumes. Nevertheless, because of the nature of the continuous simulation involved, it is at a considerably higher level, and therefore more complex, than earlier, desktop techniques.

STORM computes a runoff coefficient, CR, weighted between pervious and impervious areas by

$$CR = 0.15\ (1 - I/100) + 0.90\ (I/100) \qquad (1)$$
$$= 0.15 + 0.75\ (I/100)$$

where I is percent imperviousness and the coefficients 0.15 and 0.90 are the default values used in STORM for runoff coefficients from pervious and impervious areas, respectively. Note that in equation 1, the effect of demographic factors (e.g., land use, population density) is incorporated into the percent imperviousness, I.

A comparison of various estimating procedures indicates that the New Jersey (3) equation provides a suitable predictive equation with the population density defined as developed population density. Thus, the equation used to estimate imperviousness is

$$I = 9.8\ PD_d^{(0.377-0.0361\ \log_{10} PD_d)} \qquad (2)$$

where I = imperviousness, percent, and

PD_d = population density in developed portion of the urbanized area, persons/acre.

The simplified equation for estimating annual runoff (AR) is

$$AR = (0.15 + 0.75\ I/100)P \qquad (3)$$

where AR = annual runoff, inches/year,

I = imperviousness, percent, from equation 2, and

P = annual precipitation, inches/year.

Equation 3 can be refined by accounting for depression storage as is done in STORM. For this simplified assessment methodology, the depression storage is assumed to be as follows:

Land Use	Depression Storage, in. (cm)
Impervious	0.0625 (0.159)
Pervious	0.25 (0.635)

For a given land use, the area weighted depression storage, DS, in inches, is

$$DS = 0.25 - 0.1875\ (I/100) \qquad 0 \leq I \leq 100 \qquad (4)$$

To approximate the effect of depression storage on estimated annual runoff, one year of Minneapolis, Mn. data was simulated for varying levels of depression storage. The results indicate that a factor for depression storage can be subtracted from the original runoff equation to yield the final equation for estimating annual runoff, (5) i.e.,

$$AR = (0.13 + 0.75\ I/100)P - 5.1(DS)^{0.3937} \qquad (5)$$

where AR = annual runoff, in./yr,

I = imperviousness, percent,

P = annual precipitation, in./yr, and

DS = depression storage, in. ($0.005 \leq DS \leq 0.301$

The results, shown in Table 6, indicate average runoff of 16.5 in. (41.9 cm) per year, 14.8 in. (37.6 cm) per year, and 10.8 in. (27.4 cm) per year from an average precipitation of 31.4 in. (80.8 cm) per year in combined, storm and unsewered urban areas, respectively.

Dry-Weather Flow Prediction

Dry-weather flow is predicted based on an average flow of 100 gals per person-day (379 l per person-day). Upon multiplication by population density and conversion to appropriate units,

$$DWF = 1.34\ PD_d \qquad (6)$$

where DWF = annual dry-weather flow, in./yr, and

PD_d = developed population density, persons/acre.

Results of these calculations are shown in Table 7.

QUALITY ANALYSIS

Stormwater Quality Prediction

Quality analyses may be performed at several levels of detail, ranging from an explicit formulation of runoff quality for small subcatchments within a city to a broad representation of pollutant loads for an entire urbanized area. It may be necessary to consider the entire spectrum during the course of a study.

It is unfortunate that perhaps the only consistent remark about urban runoff quality analysis in general is that data and results of previous studies are so remarkably inconsistent. Few studies have been made of characteristics of street litter, and they offer a wide range of values of concentrations of loads. Effluent data show a similar scatter. However, it is necessary that a decision be made regarding actual values for use in the analysis. Table 8 presents a predictive equation developed after a review of available stormwater pollutant loading and effluent concentration data. The equation permits one to estimate BOD_5, SS, VS, PO_4 and N loads as a function of land use, type of sewer system, precipitation, population density, and

TABLE 6. ANNUAL WET-WEATHER RUNOFF FLOW FOR COMBINED SEWERED, NONSEWERED, AND UNSEWERED AREAS

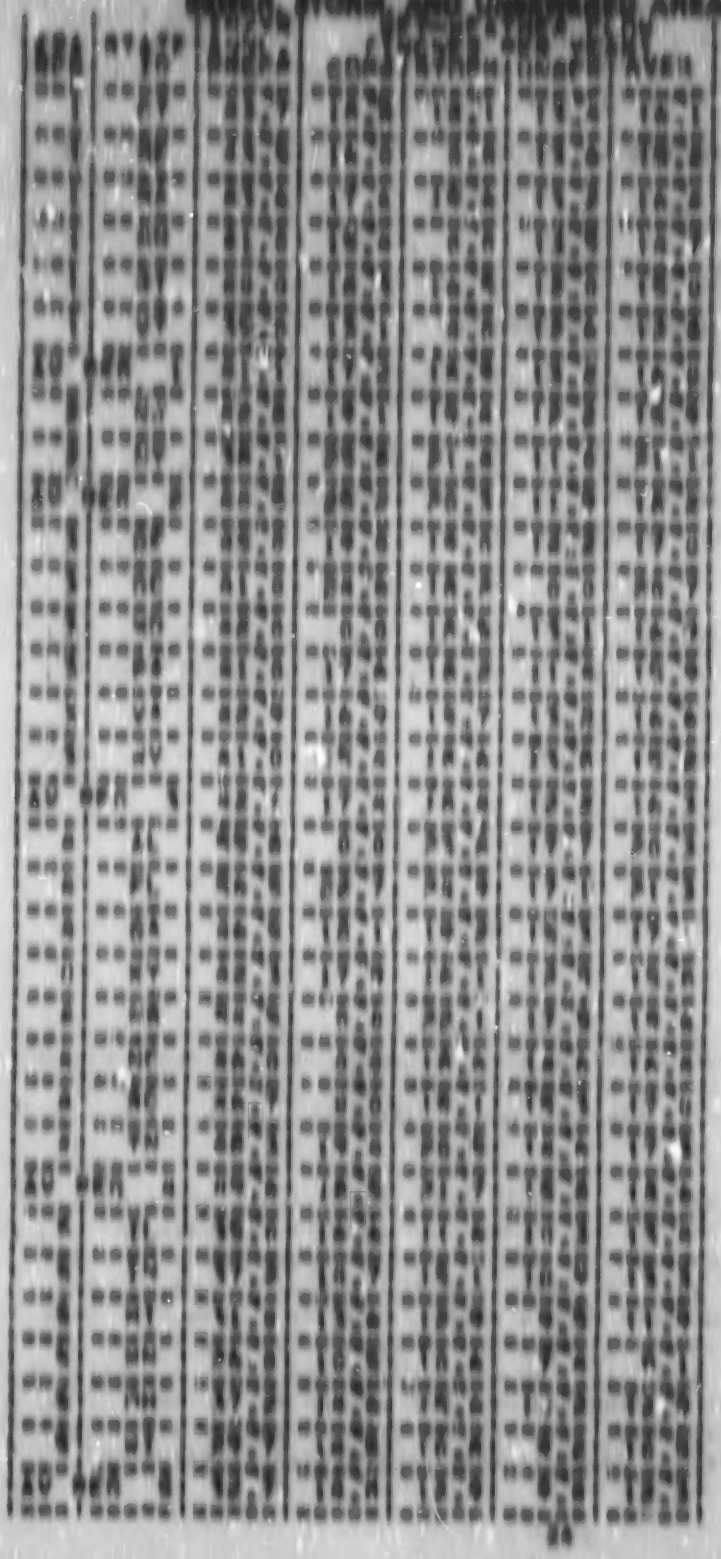

TABLE 6 (cont'd)

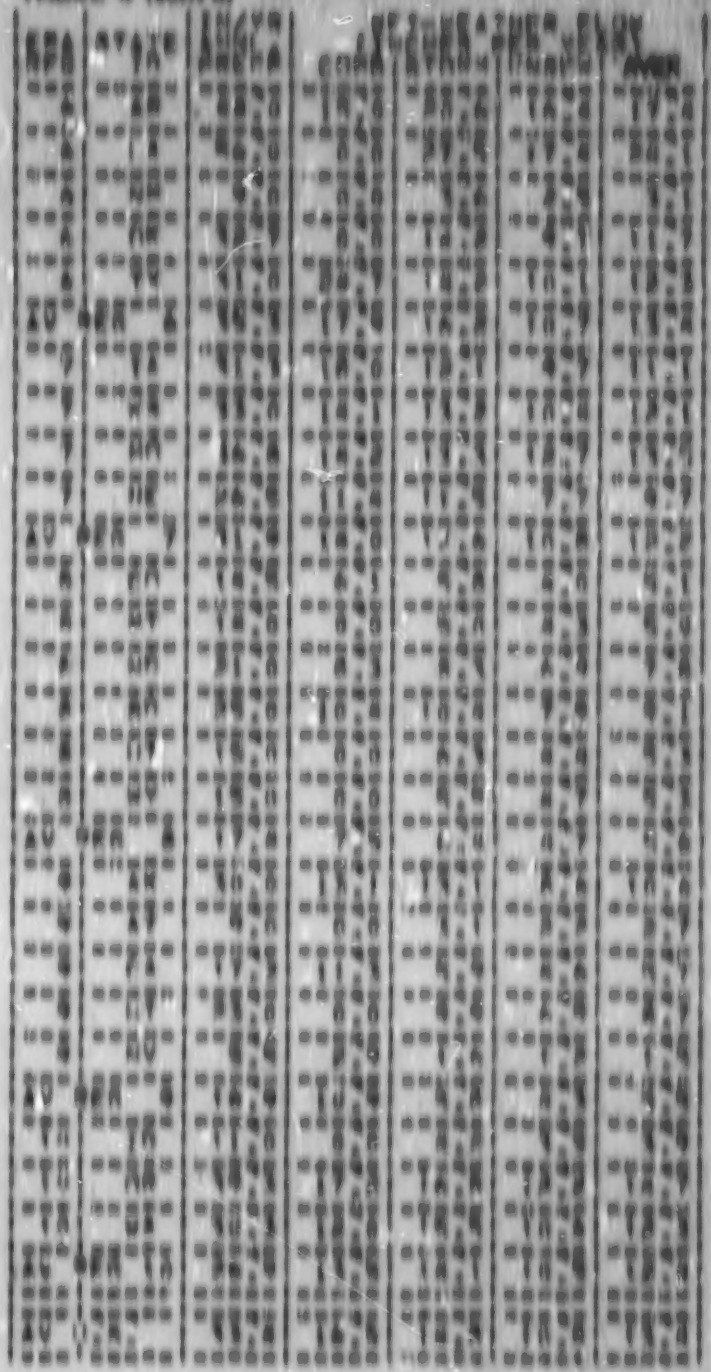

TABLE 7. ANNUAL DRY-WEATHER FLOW FOR COMBINED SEWER, STORM, AND UNSEWERED AREAS

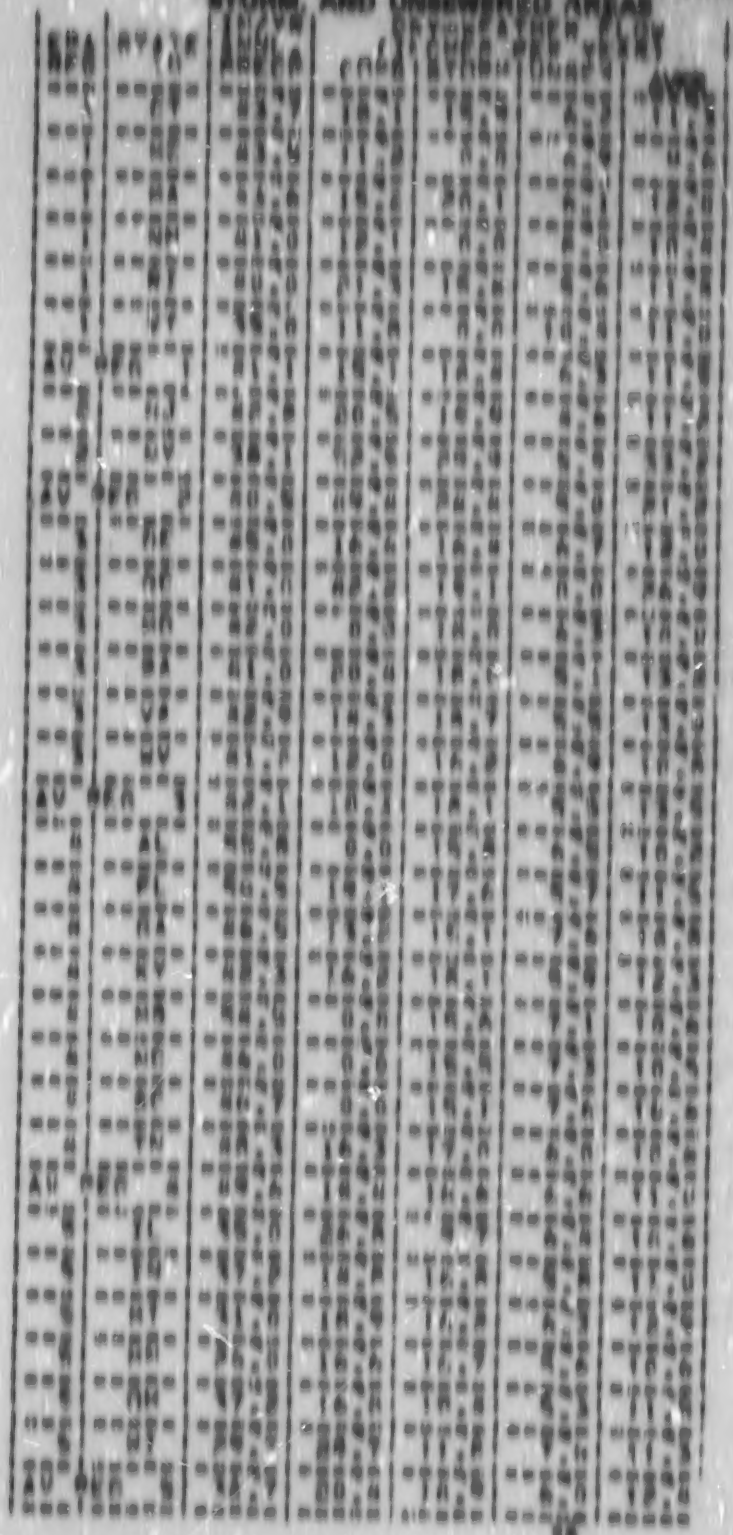

TABLE 7 (cont'd)

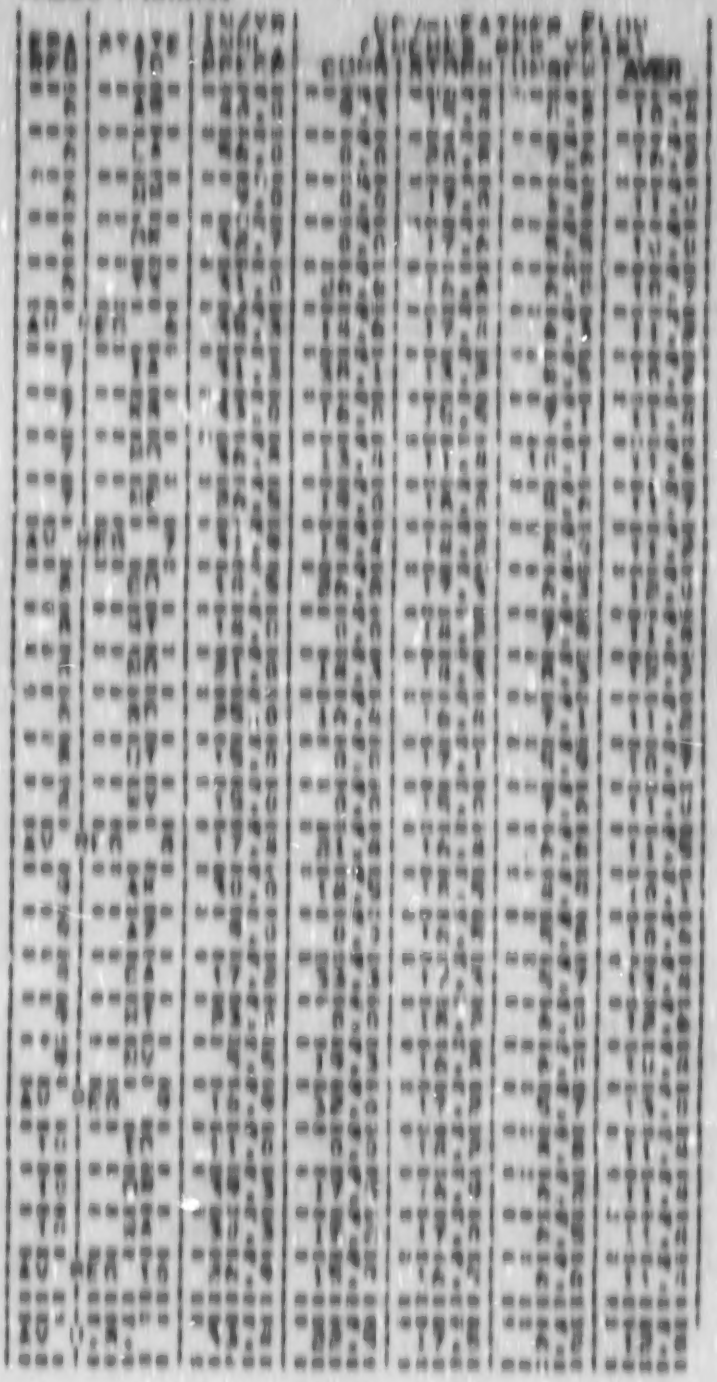

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TABLE 8. POLLUTANT LOADING FACTORS FOR NATIONWIDE ASSESSMENT

The following equations may be used to predict annual average loading rates as a function of land use, precipitation and population density.

Separate areas: $L_s = a(i,j) \cdot P \cdot S_s(PD_s) \cdot \gamma$ lb/ac-yr

Combined areas: $L_c = a(i,j) \cdot P \cdot S_c(PD_c) \cdot \gamma$ lb/ac-yr

where L = pounds of pollutant j generated per acre of land use i per year,
P = annual precipitation, inches per year,
PD = developed population density, persons per acre,
$a(i,j)$ = factors given in table below,
γ = street sweeping effectiveness factor, and
$S_s(PD_s)$ = population density function.

Land Use: 1 = Residential
2 = Commercial
3 = Industrial
4 = Other Developed (e.g., parks, cemeteries, schools (assume $PD_s = 0$))

Pollutants: 0 = BOD$_5$ Total
1 = Suspended Solids (SS)
2 = Volatile Solids, Total (VS)
3 = Total NO_3 (as N_2O_5)
4 = Total P

Population Functions: 1, 2, 3: $S_s(PD_s) = 0.199 + 0.816 \cdot PD_s^{0.54}$
4: $S_s(PD_s) = 1.0$
$S_c(PD_c) = 0.164$

Factors a and S for Equations: Separate factors, L_s and combined factors, L_c have units lb/acre-in. To convert to kg/ha-cm, multiply by 0.448.

Pollutant, j

	Land Use, i	i, BOD_5	2, SS	3, VS	4, PO_4	5, P
Separate Areas, L_s	1: Residential	0.799	16.3	2.43	0.0230	0.181
	2: Commercial	1.01	33.8	14.2	0.0717	0.199
	3: Industrial	1.11	95.1	13.2	0.0703	0.117
	4: Other	0.113	0.40	0.4	0.00004	0.0005
Combined Areas, L_c	1: Residential	3.09	87.1	20.9	0.109	0.240
	2: Commercial	13.1	93.1	17.1	0.133	1.00
	3: Industrial	5.96	170.1	19.1	0.091	1.15
	4: Other	0.469	11.3	10.0	0.0014	0.006

Street Sweeping: Factor γ is a function of street sweeping interval, N_s, (days):

$$\gamma = \begin{cases} 4_s/30 & \text{if } 0 \leq N_s \leq 30 \text{ days} \\ 1.0 & \text{if } N_s > 30 \text{ days} \end{cases}$$

street sweeping frequency. Loadings in combined sewer areas are assumed to be 4.16 times as large as loadings in separate areas based on measured pollutant loads from those areas. They are assumed to vary as a function of developed population density. The intercept (0.168) was determined based on data for open space. The exponent (0.54) is based on the exponent of the imperviousness equation at a population density of 9 persons per acre (20 persons per ha) such that pollutant concentration increases as a function of population density. Lastly, the coefficient (0.318) is based on an average of data points with a PD_d ranging from 5 to 15 persons per acre (12 to 37 persons per ha) to yield a value of $F_3(PD_d)$ of 0.895 at 10 persons per acre (25 persons per ha). The street sweeping relationship was derived by making numerous runs of STORM with varying street sweeping frequencies.

Nationwide Quality Assessment

Annual BOD_5 loads were calculated for the 348 urbanized areas for both wet and dry-weather conditions, the latter under the assumption of 0.17 lb per person-day (0.08 kg per person-day). The national summary is shown in Tables 9 and 10. Loading rates for untreated dry-weather flow are higher than for wet-weather flow. However, if 85 percent secondary treatment is assumed for dry-weather BOD generation, wet-weather loads are seen to be one third of the total residual loadings in urban areas. Moreover, BOD loadings from combined sewered areas are comparable to loads due to secondary effluent.

COST ASSESSMENT METHODOLOGY

Control Technology and Associated Costs

A wide variety of control alternatives are available for improving the quality of wet-weather flows. (7,8,9) Rooftop and parking lot storage, surface and underground tanks, in-line storage, and storage in treatment units are used to control the flow. Wet-weather quality control alternatives can be subdivided into two categories: primary devices and secondary devices. Primary devices take advantage of physical processes such as screening, settling and flotation. Secondary devices take advantage of biological processes and physical-chemical processes. These control devices are suitable for treating stormwater runoff as well as combined sewer overflows. At the present time, there are several installations throughout the U.S. designed to evaluate the effectiveness of various primary and secondary devices. Based on these data, the representative performance of primary devices is assumed to be 40 percent BOD_5 removal efficiency and that of secondary devices to be 85 percent BOD_5 removal efficiency.

"Storage" devices will typically be used in conjunction with the above "treatment" devices. The two purposes are interrelated. Wastewater detained a sufficient time in a storage unit will undergo treatment. On the other hand, treatment units also function as storage units in that they equalize fluctuations in influent flow and concentration. The STORM model, which was used in this assessment, assumes that no treatment occurs in storage and "treatment"

TABLE 9. DRY-WEATHER SOD LOADINGS

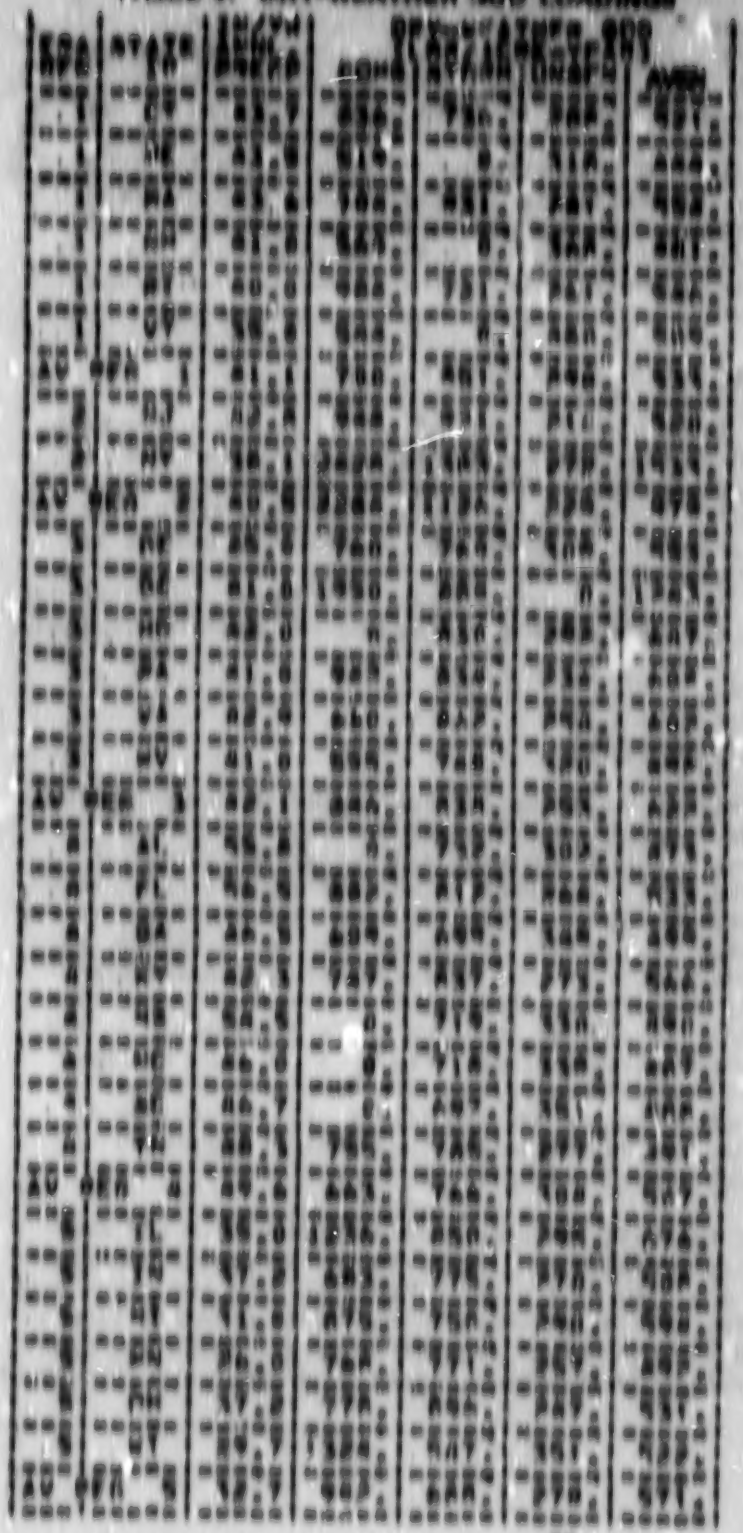
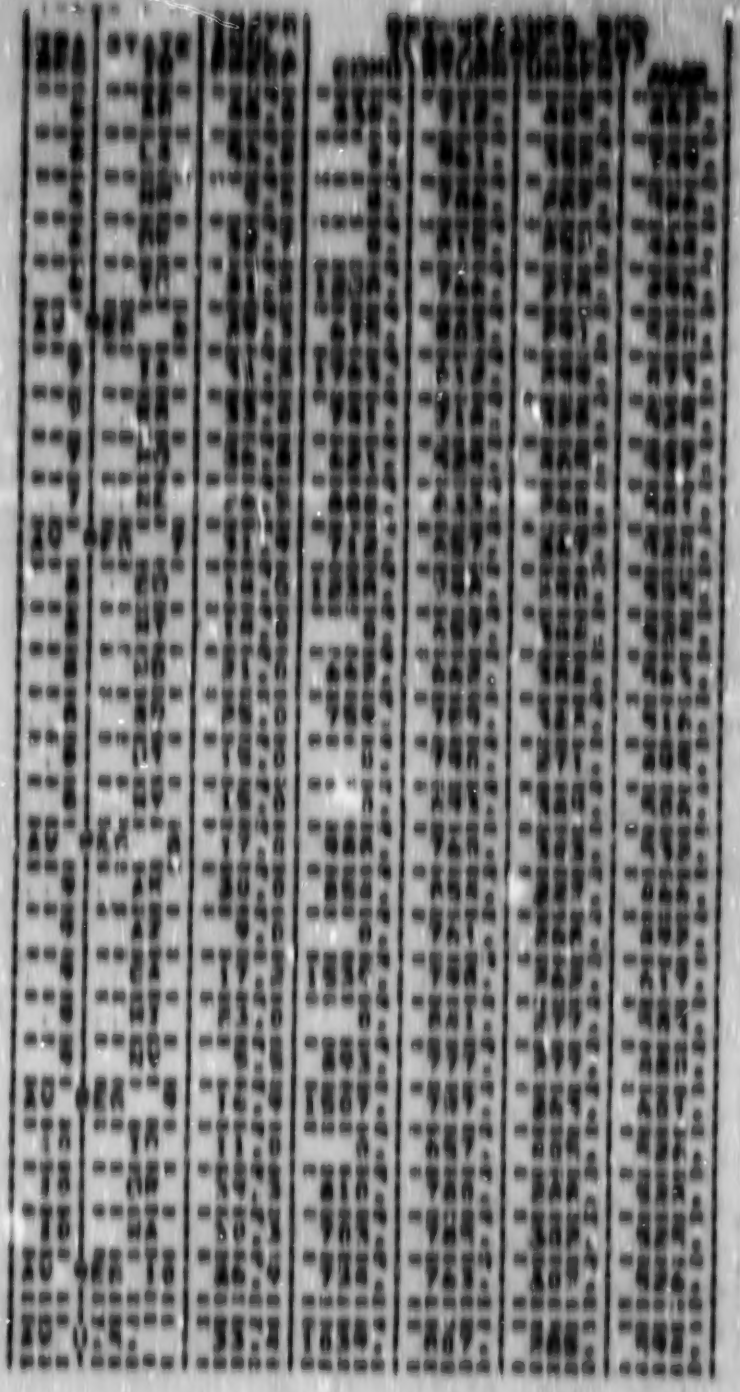
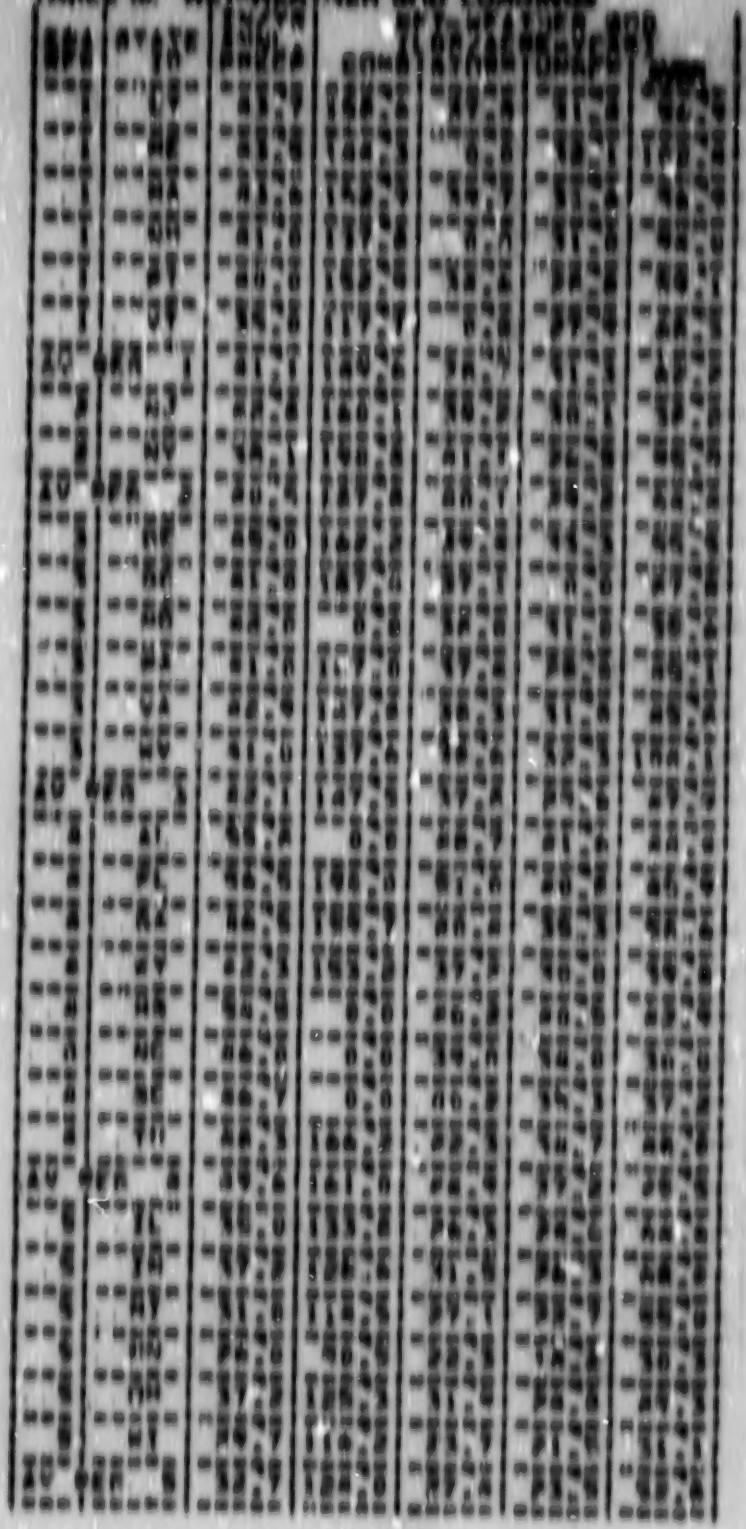
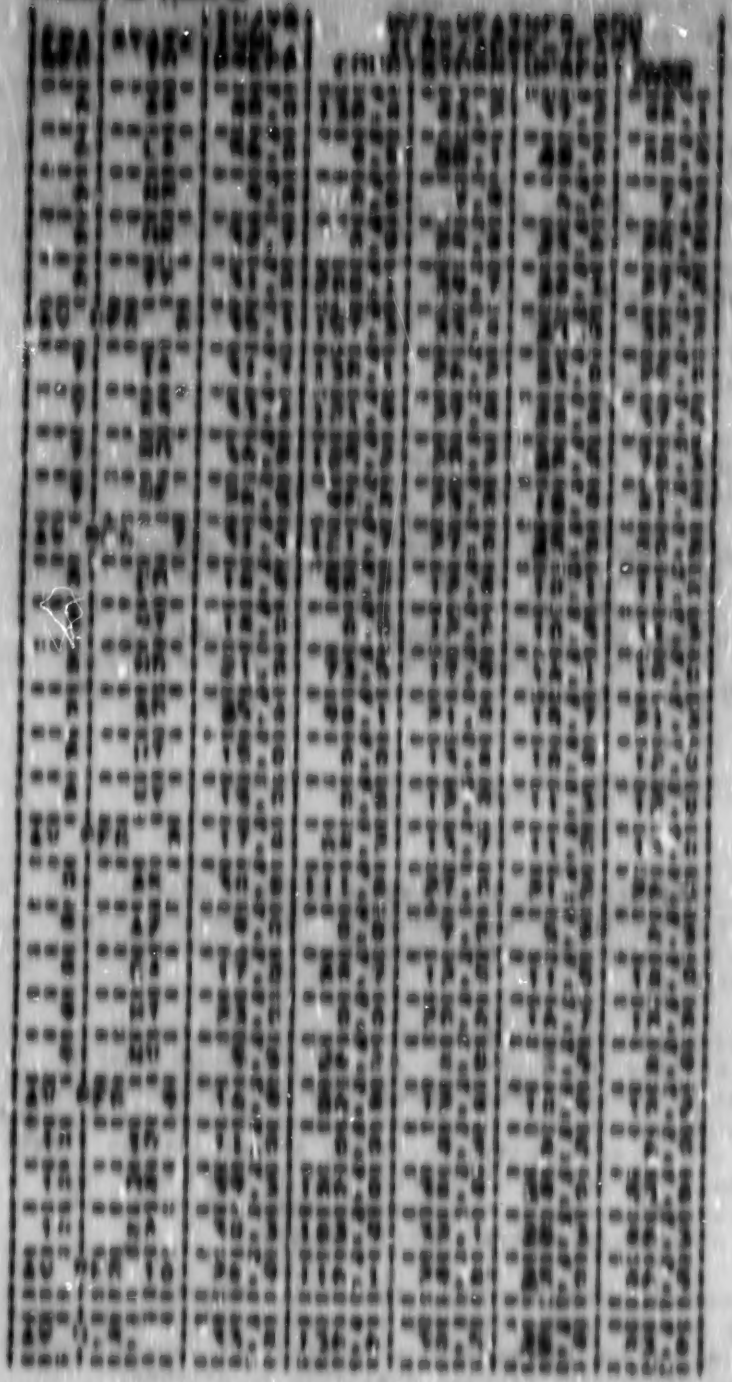


TABLE 9 (continued)







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is assumed to be complete removal of all pollutants routed through treatment. That, for the purposes of this assessment, no treatment is assumed to occur in storage and control costs are assigned accordingly. This assumption tends to underestimate the costs of storage since all provisions for solids handling are included in treatment.

Cost of Treatment and Storage

Cost functions developed for various wet-weather quality control devices are presented in Table 11. These costs include provisions for sludge handling, engineering, contingencies and land costs. All treatment units exhibit economies of scale, i.e., unit costs decrease as plant size increases. Thus, there is an incentive to build larger units. The optimal size treatment unit can be found by comparing the savings in treatment cost of going to a larger unit with the increased piping costs.

For this analysis the number and flow rate of stormwater discharges in urban areas were unknown. Thus, it is not possible to determine the optimal mix of treatment plants and pipelines. Therefore, representative annual treatment costs of $4,000 per mgd for primary devices and $15,000 per mgd ($1,057/m^3) for secondary devices were used. Review of data on the cost of storage indicated wide variation. Thus, the relatively simple relationship shown in Table 11 was used. Annual storage costs are estimated as a function of gross population density. The curve was derived using an unamortized capital cost of $0.10 per gal ($0.026 per l) for PD = 5 persons per acre (12.4 persons per ha) and $0.30 per gal ($0.13? per l) for PD = 15 persons per acre (37.1 persons per ha).

Relationship Between Storage/Treatment and Percent Pollution Control

STORM(3,4) was used to evaluate various storage/treatment options for controlling stormwater runoff pollution. This model assumes that the study area can be characterized as a single catchment from which hourly runoff is directed to storage and treatment.

STORM uses a simplified rainfall/runoff relationship, neglects the transport of water through the city and assumes a very simple relationship between storage and treatment. However, these simplifications are essential if one hopes to do a continuous simulation. The continuous simulation approach was used because no general concurrence exists regarding an appropriate single event that one should analyze. The degree of control can be expressed in terms of the percent of the runoff treated, the annual number of overflows, or the amount of pollutants discharged to the receiving water.

As described in the User's Manual, STORM computes the runoff based on the composite runoff coefficient and the effective precipitation. (3) The depression storage must be satisfied before the runoff coefficient is applied to the precipitation. The amount of depression storage available in ditches, depressions, and other surfaces is a function of the past precipitation and the evaporation rates. Each hour that runoff occurs, the model compares it

TABLE 11. COST FUNCTIONS FOR WET WEATHER CONTROL DEVICES

Device	General Alternative	Annualized Capital		Annual Costs, $/yr: Operation and Maintenance		Total	
		a	b	a	b	a	b
Primary	[illegible]	1,871.0	0.74	467.0	0.70	2,338.0	0.72
	Microstrainer[a,f]	7,013.0	0.74	1,838.0	0.70	8,173.0	0.72
	Dissolved Air Flotation[b]	8,161.4	0.81	2,038.7	0.81	10,199.1	0.81
	Sedimentation[c]	32,634.7	0.73	8,157.8	0.70	40,792.5	0.72
	Representative Primary Device – Total Annual Cost = $4,000 (at mgd ($0.793/m^3/day)						
Secondary	Contact Stabilization[d]	19,980.7	0.66	4,994.7	0.65	24,480.4	0.65
	Physical-Chemical[e]	32,634.7	0.66	8,157.8	0.65	40,792.5	0.65
	Representative Secondary Device Total Annual Cost = $19,000 per mgd ($3.83/m^3/day)						
Storage	High Density (15/ac)	31,000.0	1.00	---	---	31,000.0	1.00
	Low Density (6/ac)	10,700.0	1.00	---	---	10,700.0	1.00
	Parking Lot[g]	10,200.0	1.00	---	---	10,200.0	1.00
	Rooftop[h]	5,100.0	1.00	---	---	5,100.0	1.00
	Representative Annual Storage Cost[i] ($ per ac-in) = $123 $p^{0.19(PD)}$						

Q^b = Wet Weather Treatment Rate in mgd; S^1 = storage Volume in mg

[a]AACE = 5.000. Includes land costs, chlorination, sludge handling, engineering and contingencies.

[b]Sludge handling costs based on data from Eckenfelder, 1974.[14]

[c]Field and Masta, 1978.[11]

[d]Benton, et al., 1978.[12]

[e]Lager and Smith, 1974.[9]

[f]Metcalf, 1974.[13]

[g]Agnew et al., 1978.[10]

[h]Holscott and Robbins, 1975.[15]

[i]For $Y \leq 1.00$ mgd. No economies of scale beyond 100 mgd (378,500 m^3/day).

[j]PD = in-use population density, acres/acre

[k]One mgd = 3,785 m^3/day.

[l]One ac = 0.405 m^2.

to the treatment rate. As long as the runoff rate is less than or equal to the treatment rate all the runoff passes directly through the treatment plant and storage is not utilized. When the runoff rate exceeds the treatment rate, the excess runoff is sent to storage. If excess runoff occurs frequently enough to exceed the storage capacity then overflow occurs. When runoff falls below the treatment rate then storage is depleted at the excess treatment rate. The hourly occurrence of treated runoff, stored runoff, and runoff that has overflowed is tabulated for the entire record of rainfall. Included in the output is the annual number of overflow events and the percentage of the runoff that overflowed to the receiving waters. This type of analysis was carried out for different storage capacities and treatment rates.

STORM Input Data for Detailed Study of Five Test Cities

STORM requires several input parameters that characterize the urban area under study. These include hourly precipitation, total area, land use types and percentages, percent imperviousness and curb length per area for each land use. Local data used to run STORM on the five study areas were collected by onsite interviews. The percent imperviousness and length of street gutters were found by their relationship to population density using Stankowski's equation for imperviousness(3) and ASCE's equation for curb length density, i.e.,

$$a_L = 0.0783 - 0.0868(0.839)^{PD_d} \qquad (7)$$

where a_L = curb length per area, miles/acre, and

PD_d = developed population density, persons/acre.

Daily evaporation rates for each month are from a report by Thornthwaite and Mather.(16) The depression storage was assumed to be 0.01 in. (0.025 cm) for all cities. Hourly precipitation data were required from the US Environmental Data Service in Asheville, North Carolina. Twenty-five years (January, 1948, to December, 1972) of hourly data were obtained for the five test cities. Two and one-half years (July, 1970, to December, 1972) of data were obtained for all stations in the United States.

The frequency distribution of each of the twenty-five years of rainfall was analyzed for each of the five cities. Little year-to-year variation in distributions was noted, but there was considerable variation among cities.

In the early stages of the research it became apparent that multiple runs of STORM would be required on each city to adequately determine the effectiveness of different storage capacities and treatment rates. It was also discovered that making STORM runs using the entire twenty-five years of rainfall for each city was expensive and time consuming. Since the useful information was in terms of the overall level of control of the runoff, it appeared adequate to run STORM on a single year if the results were the same as running STORM for the entire twenty-five year period.

Results

Storage/Treatment Isoquants--

For each storage/treatment rate combination, there is a value for the percent of the runoff and pollutants which are "treated". By making several runs at different combinations of treatment and storage, points were generated representing different levels of control. Then isoquants were drawn connecting the points that represent combinations of storage capacities and treatment rates which give equivalent percent runoff and/or pollutants "treated". If the concentration of pollutants is constant and "treatment" efficiency is 1.0, then percent runoff control is synonymous with percent pollutant control. Obviously, this is not the case. Thus, account needs to be taken of --

1. treatment efficiency, and
2. variable concentration due to first-flush effects.

Adjustment for Treatment Efficiency--

Let R denote the percent runoff control and η equal treatment plant efficiency. If R_1 denotes the percent pollutant control, then to realize R_1 one needs to process R_1/η of the runoff. Note that R_1 may be percent BOD removal, percent SS removal, etc. The following representative treatment efficiencies, in terms of BOD_5 removal, were assumed for primary and secondary devices.

Treatment Device	Assumed Efficiency, η (BOD Removal)
Primary	0.40
Secondary	0.85

Thus, if one desires 35 percent BOD_5 removal with a primary device, then 87.5 percent of the runoff volume must be processed whereas only 41.4 percent of the runoff needs to be processed if a secondary device is selected. Thus, to convert percent runoff control isoquants to percent pollutant control isoquants, one uses --

$$R = \frac{R_1}{\eta}, \quad 0 \leq R \leq 100 \tag{5}$$

Adjustment for First Flush --

STORM estimates the percent pollutant control as well as percent runoff control. The STORM runs incorporated the standard first flush assumption which is used in the model, i.e., the amount of pollutant removal at any time, t, is proportional to the amount remaining and that a uniform runoff of 0.5 in. (1.3 cm) per hour would wash away 90 percent of the pollutant in one hour.(5) If a first flush is assumed, then storage and treatment can be operated more

effectively because of the greater relative importance of capturing the initial runoff. The first flush is accounted for by defining the output in terms of pollutant control directly.

Mathematical Representation of Isoquants --

The storage/treatment isoquants are of the form

$$T = T_1 + (T_2 - T_1)e^{-KR} \quad (9)$$

where T = wet-weather treatment rate, inches per hour,

T_1 = treatment rate at which isoquant becomes asymptotic to the ordinate, inches per hour,

T_2 = treatment rate at which isoquant intersects the abscissa, inches per hour,

R = storage volume, inches, and

K = constant, $inch^{-1}$.

A relatively large storage reservoir is required to operate the treatment unit continuously. Thus first flush effects would be dampened out and the effluent concentration from the reservoir should be relatively uniform. Thus, if stormwater entering the treatment plant has a relatively uniform concentration, then T_1 can be found as follows for 8,760 hours per year:

$$T_1 = \frac{AR}{8760}\left(\frac{R}{100}\right) = aR \quad (10)$$

where AR = annual runoff, in. per year,

a = coefficient defined by AR and conversion factors, and

R = percent runoff control.

By relating the parameters T_1, T_2-T_1 and K to the level of control R, one equation was developed for each of the five cities. The T_2-T_1 and K terms versus R were found to be of the following general form:

$$T_2 - T_1 = be^{hR} \quad (11)$$

$$K = de^{-fR} \quad (12)$$

Based on this analysis the following general equation for the isoquants is obtained:

$$T = aR + be^{hR-(de^{-fR})R} \quad (13)$$

The values of parameters a, b, h, d and f for various cities are presented in Table 13. The correlation coefficients for each fit were all above 0.99.

[illegible]

[illegible]

[illegible]

[illegible]	a	b	c	d	e
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The results for Minneapolis, presented in Figure 1, show the isoquants calculated by the foregoing equation. Also shown are some actual data points for a treatment rate of 0.01 in. (0.025 cm) per hour and varying amounts of storage. The boundaries of the five regions are shown in Figure 2.

The optimal expansion path can be found using

$$\frac{c_s}{c_t} = MRS_{ST} \tag{14}$$

where c_s = unit cost of storage,

c_t = unit cost of treatment, and

MRS_{ST} = marginal rate of substitution of storage for treatment.

A generalized method for evaluating the optimal mix of storage and treatment for any desired level of pollutant control has been presented. This method can be used for any city in the United States to obtain a first approximation of control costs. Five cities (Atlanta, Denver, Minneapolis, San Francisco, and Washington, DC) were used in the more detailed analysis. The effects of treatment plant efficiency and first flush are included.

An evaluation was made of the relative desirability of using a mix of storage with either primary treatment or secondary treatment. The basic tradeoff to be evaluated is whether primary treatment is sufficiently less expensive than secondary treatment to offset its lower removal efficiency which necessitates treating a much larger amount of flow to effect an equivalent BOD removal. The results indicate that a primary type of facility is preferable up to BOD removals of about ten percent. A secondary facility is preferable for higher levels of control.

The annual average percent runoff control and the annual number of overflow events were correlated to permit the reader to use either criterion as an effectiveness metric. A precipitation event was assumed to terminate following 12 hours of no precipitation.

The final assessment results (annual costs per acre) are shown in Tables 13, 14, and 15. In order to obtain an overall wet-weather pollutant control of, say, 50 percent in a given urbanized area, the optimal strategy is to use a blend of control in the combined, storm, and unsewered portions of the urbanized areas such that the marginal costs of control in each of these three areas is equal. The results are shown in Table 16. Knowing this result and the control cost equations for each type of sewerage system in each urbanized area, the optimal cost per acre can be determined as shown in Table 17. Lastly, the costs per acre are multiplied by the acreage in the combined, storm, and unsewered categories to obtain the final assessment results which are shown in Table 18. The results indicate that, for the entire U.S., the total annual costs for 35

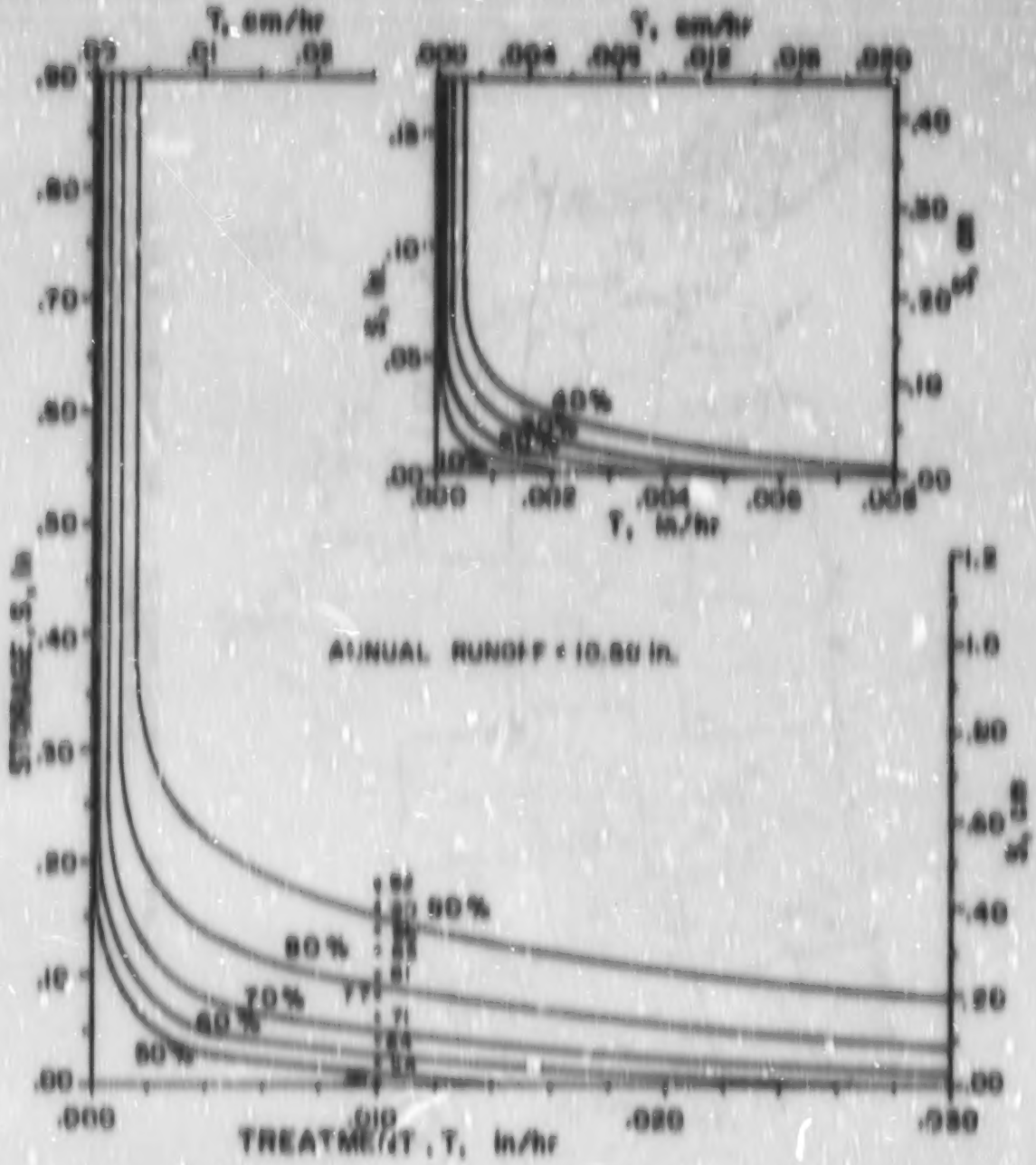

Figure 1. Storage/treatment loss rate for percent $(n-1)_0$ removal with first flush — Region III - Minneapolis

Figure 2 [illegible]

Source [illegible]

TABLE 19. ANNUAL CONTROL COSTS--COMBINED AREAS

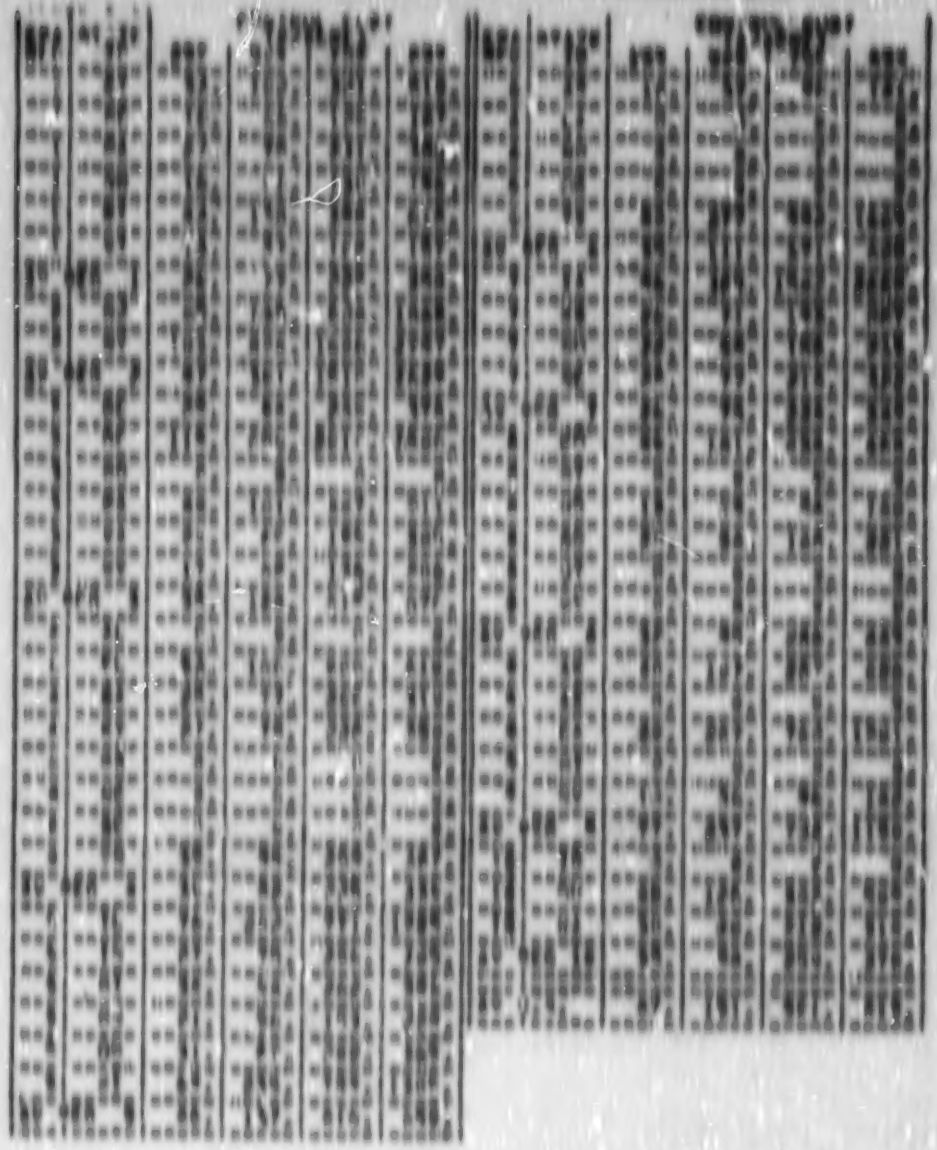

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TABLE 14. ANNUAL CONTROL COSTS-STORM SEWERED AREAS

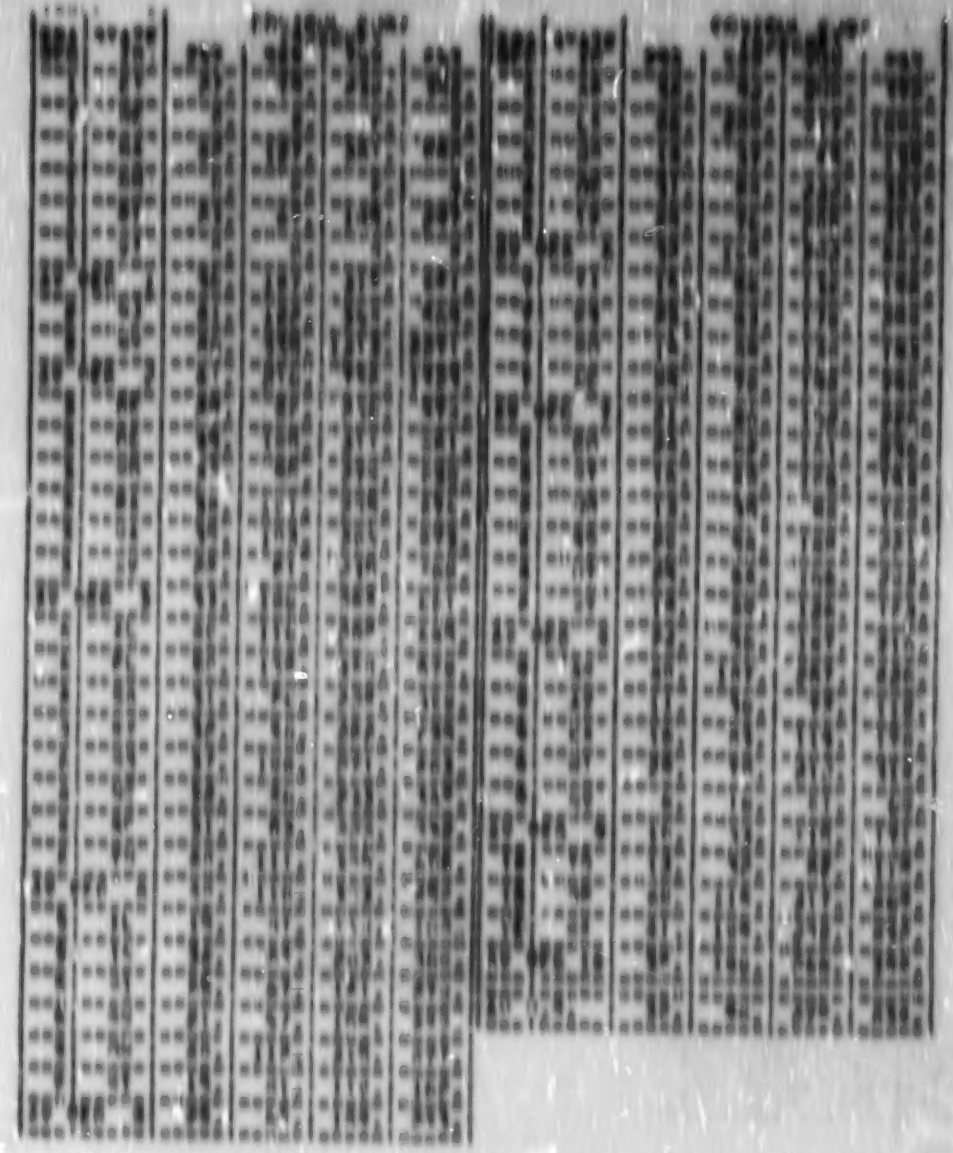

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TABLE 15. ANNUAL CONTROL COSTS-UNSEWERED AREAS

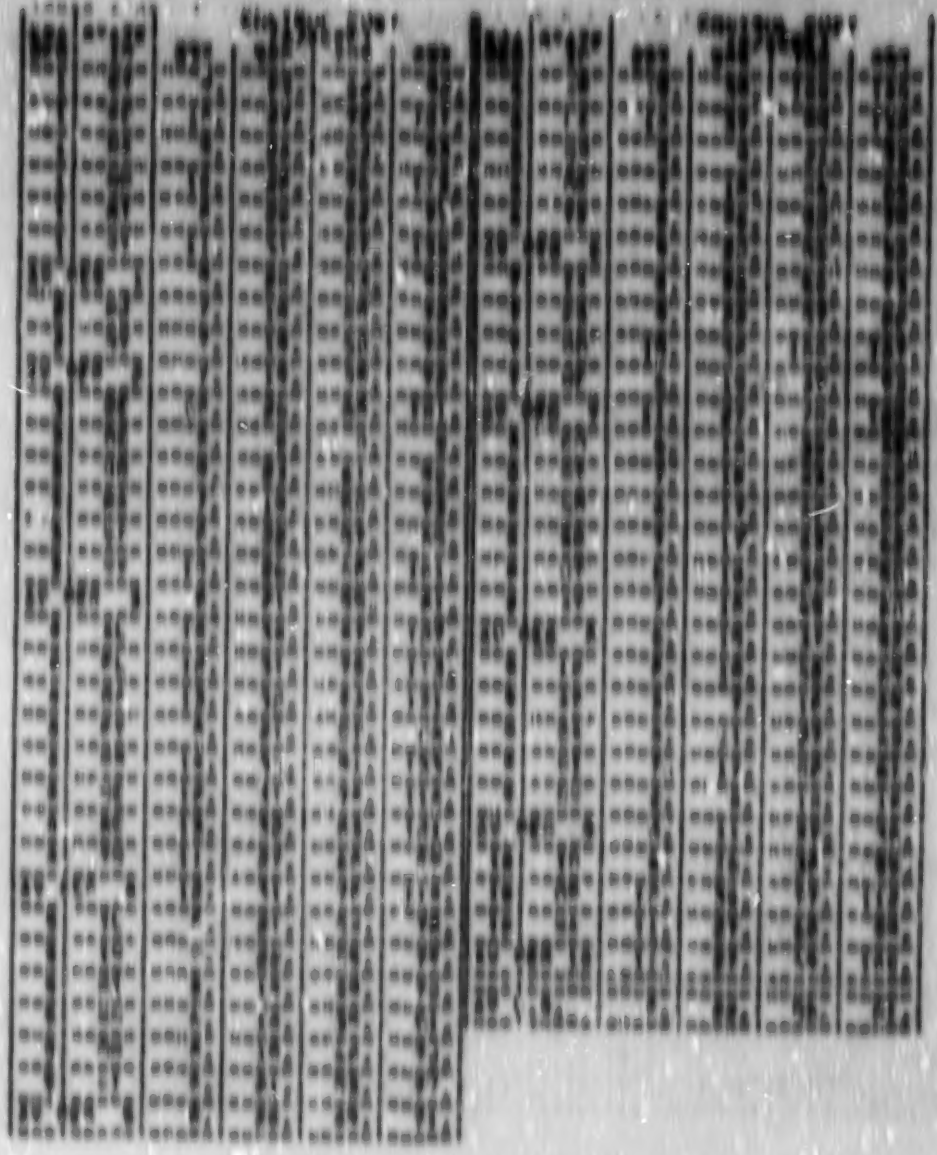

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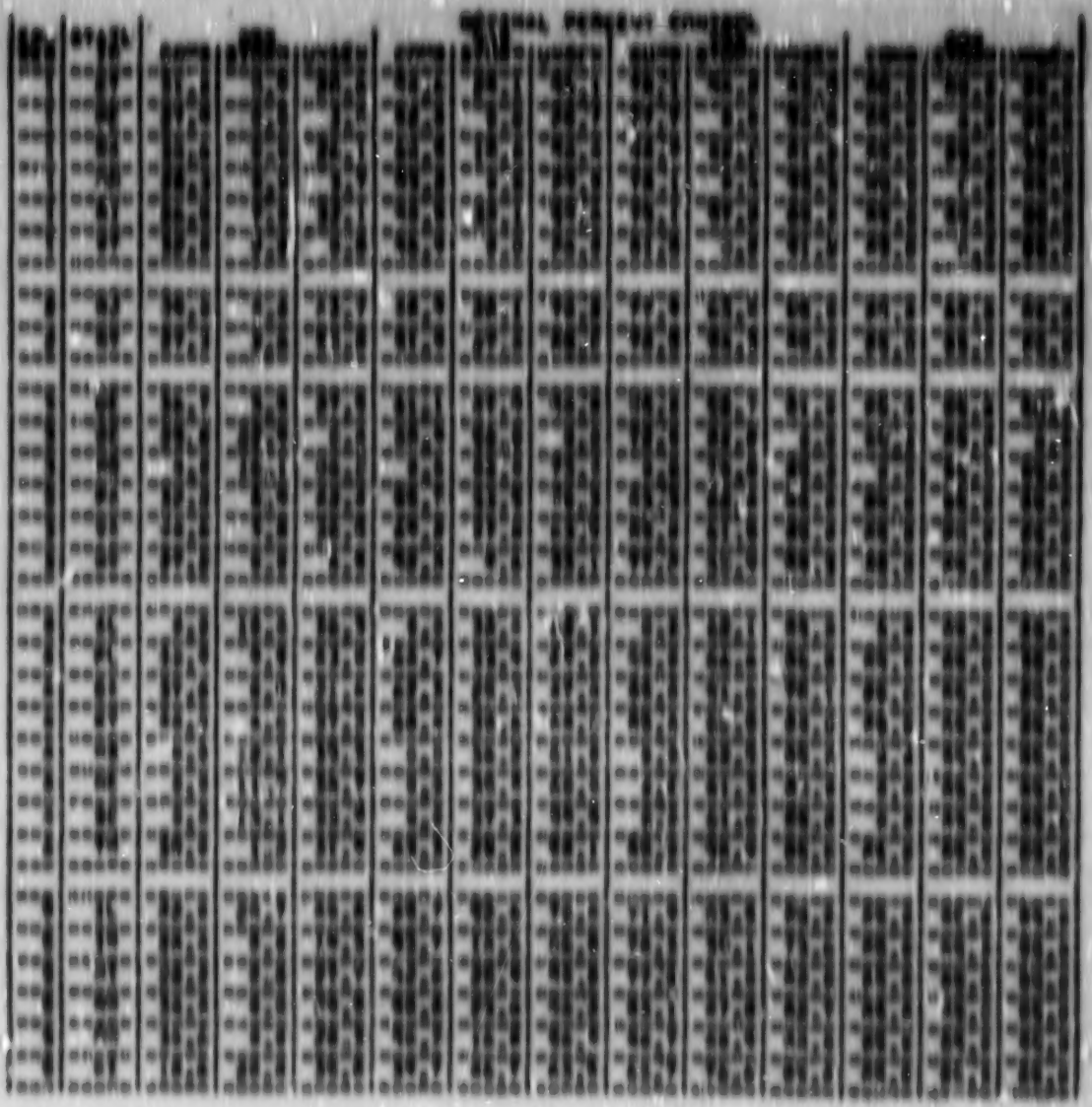
TABLE 16. OPTIMAL PERCENT CONTROL FOR SPECIFIED OVERALL CONTROL



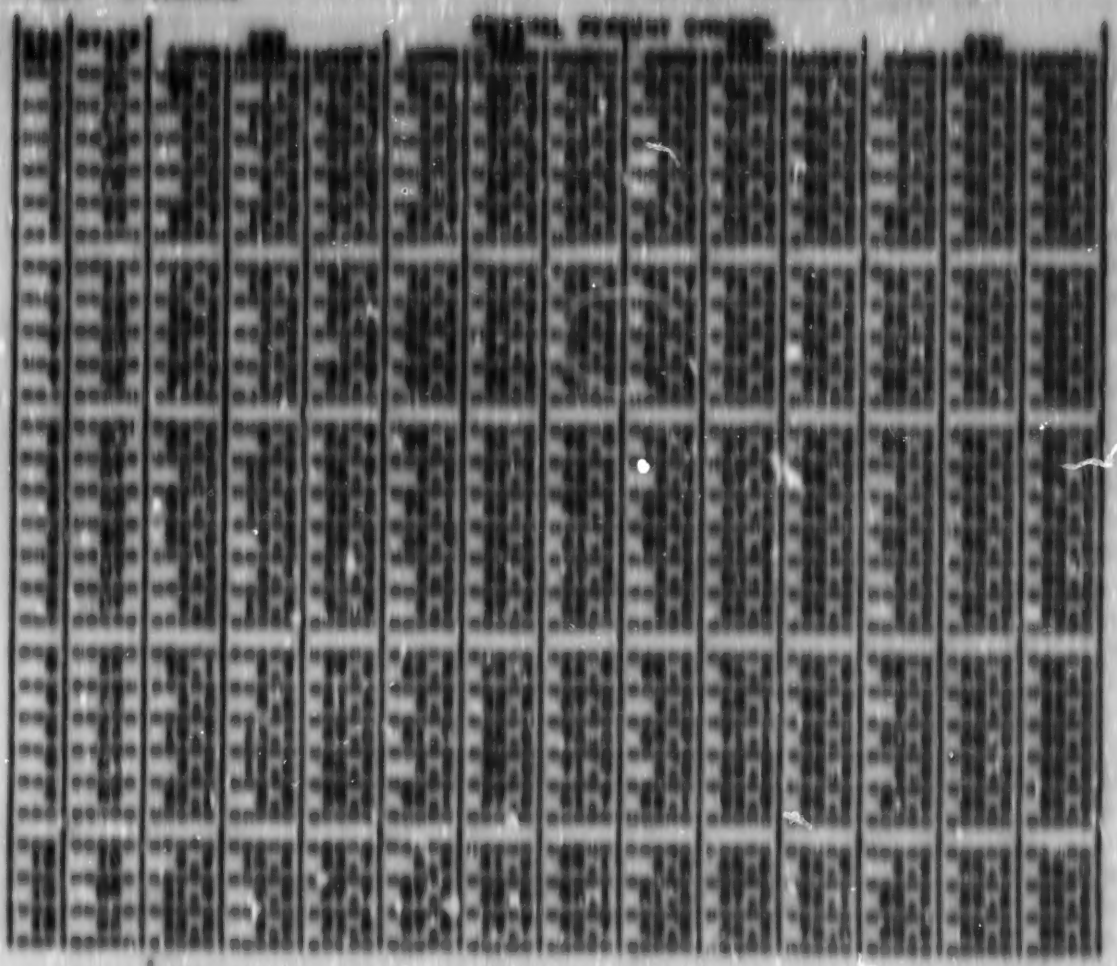


TABLE 17. OPTIMAL ANNUAL COST PER ACRE FOR SPECIFIED OVERALL FREQUENCY CONTROL

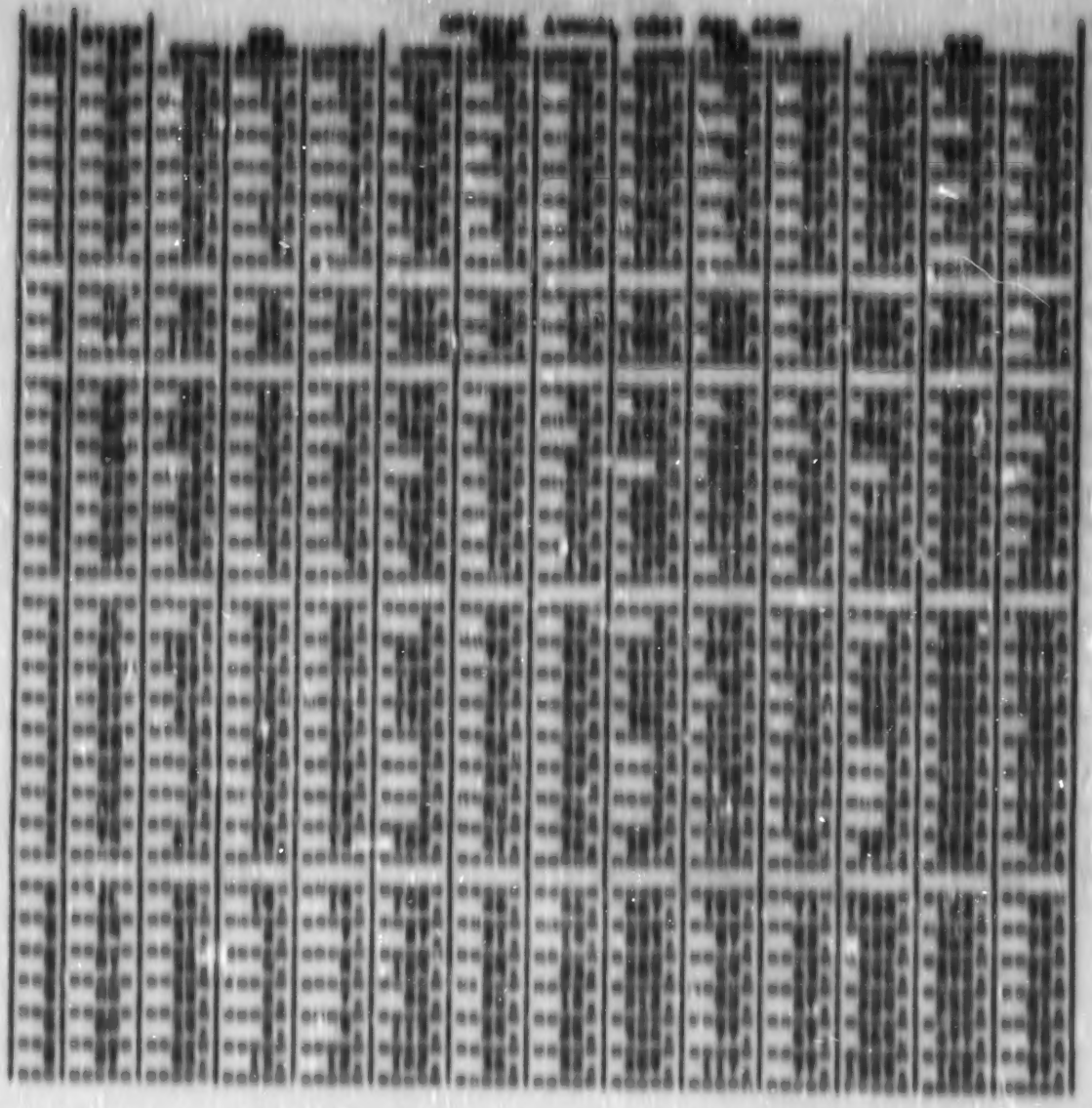


TABLE 17 (cont'd)

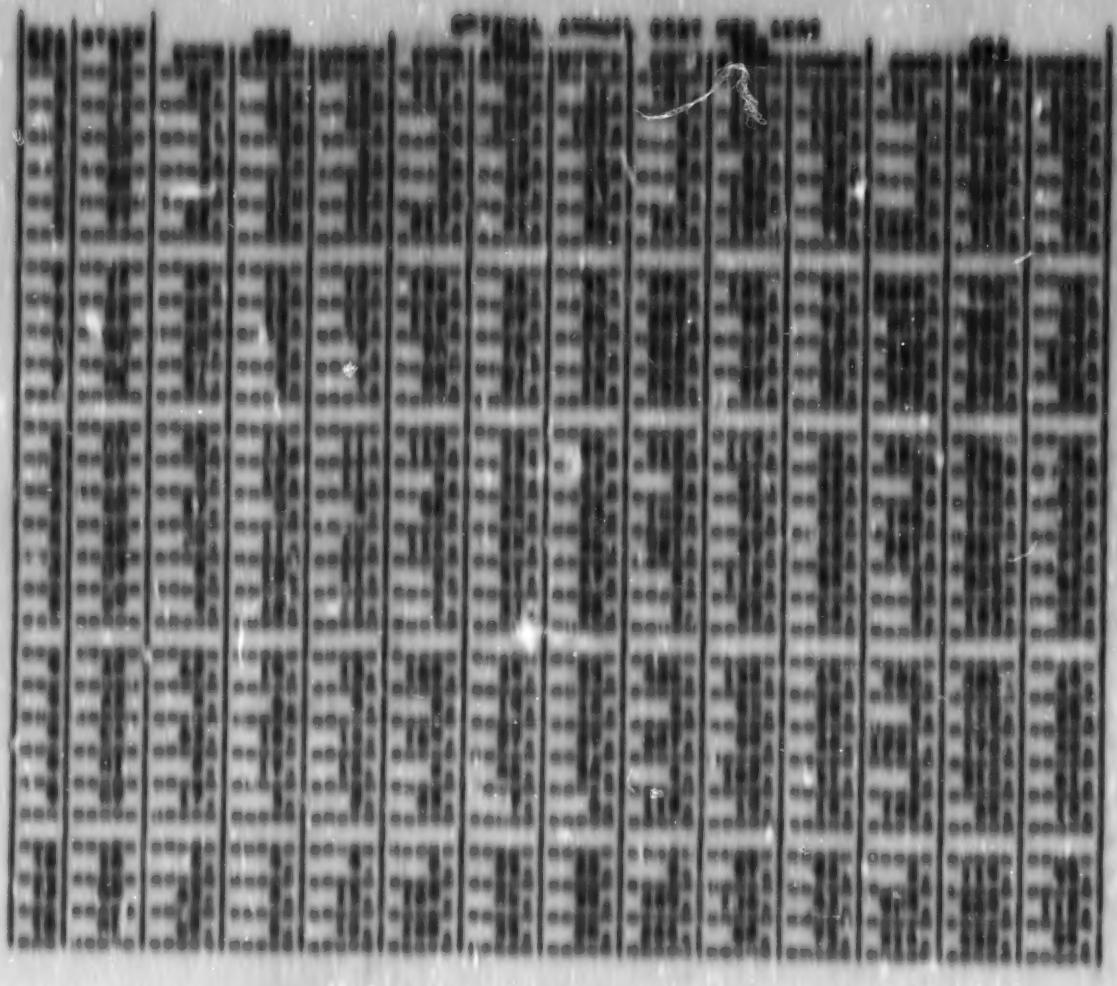


TABLE 18. OPTICAL ARRIVAL AND CAPTIVE CONTACT SITES

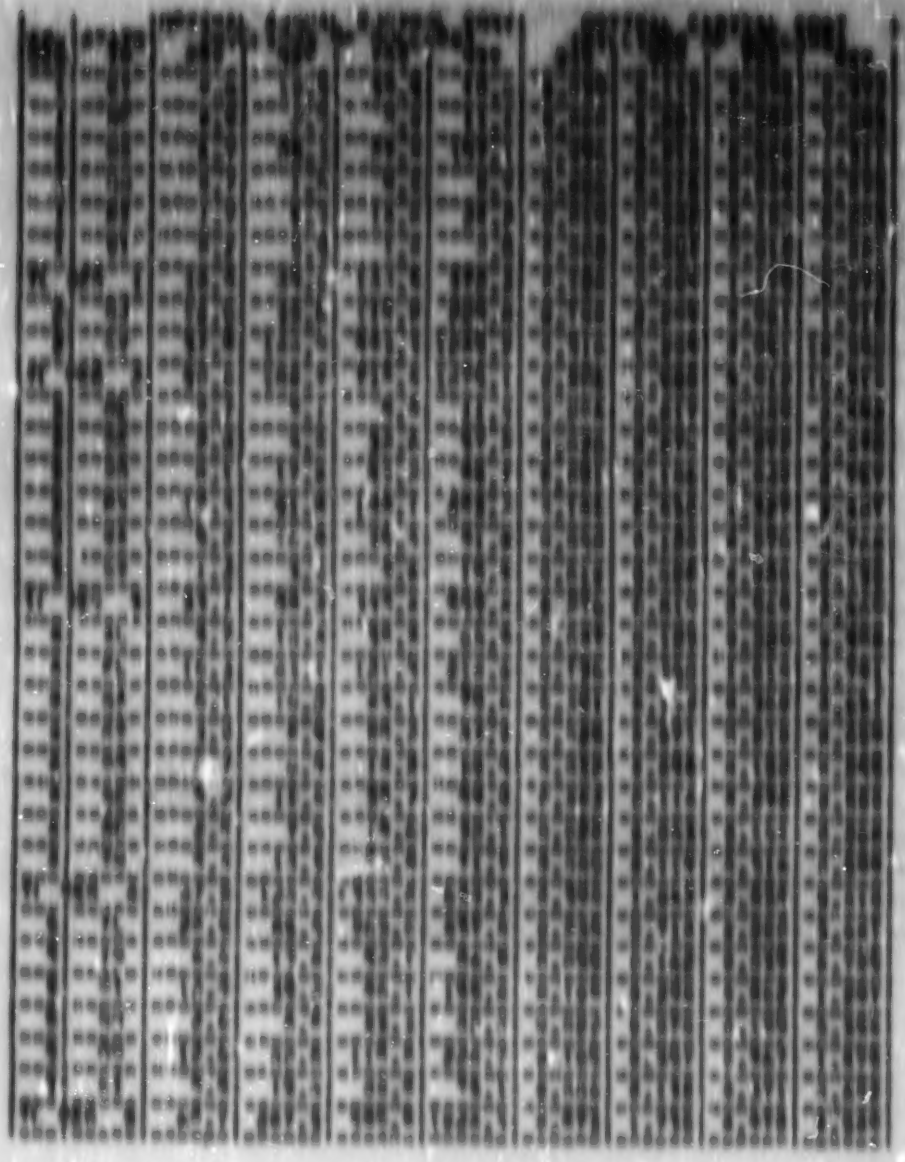


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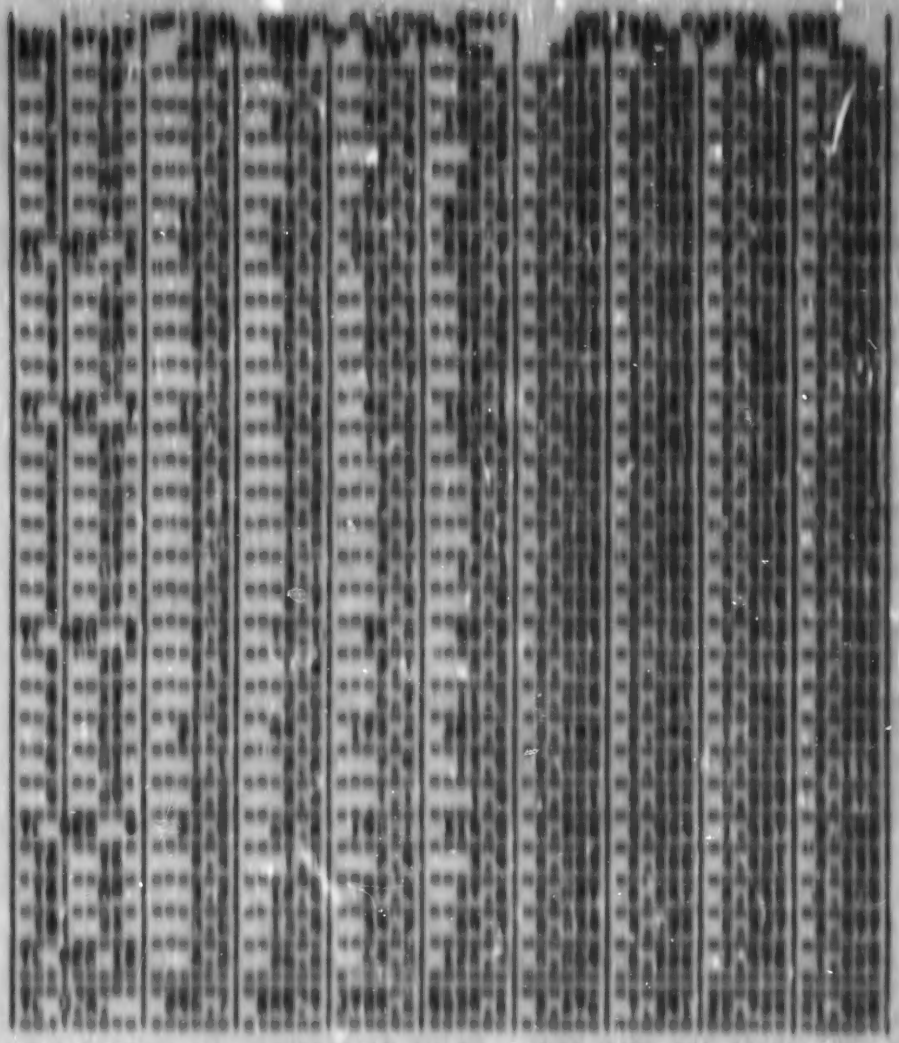
TABLE 10 (cont'd)



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50, 75, and 85 percent BOD control are $797, $888, $1,733, and $5,919 millions of dollars per year. Similarly, the initial capital investment for 65, 90, 95, and 85 percent BOD control is $5,475, $7,101, $22,746, and $61,048 millions of dollars based on 85 percent of the present worth of the total annual cost at an assumed interest rate of 8 percent over 30 years. Note that the incremental costs for wet-weather control increase significantly. This is due to the disproportionately larger control units needed to capture the less frequent, larger storms.

An analysis was made of the possibility of cost allocation among wet-weather quality control and dry-weather quality control (with fire equalization) and dry-weather quantity control (with storage required to reduce run-off rates and volumes). The results suggest that significant savings might be realized as shown in Figure 5, which indicates reductions ranging from 70 percent at low control levels to 30 percent at high levels.

In addition to using storage/treatment devices to control wet-weather pollution, other management practices are available. A related study suggests that significant savings in control costs could be realized if other management practices are used in conjunction with storage/treatment. (17) The estimated costs of control incorporating other management practices are shown in Figure 5. The savings range from about 30 percent at low levels of control to about 95 percent at higher control levels. Further savings could be realized by allocating some of the cost to other purposes, e.g., street sweeping for aesthetics.

The relationship between tertiary treatment and wet-weather control was examined by finding the percent wet-weather control to initiate prior to using tertiary treatment. Results indicate that about 4 percent of the wet-weather flow problem should be controlled before initiating tertiary treatment control. BOD removal was used as the effectiveness metric. Different results would be obtained using nutrient control as the criterion.

The results of this assessment indicate significantly lower control costs than reported in earlier studies, i.e., the MSDGC Needs survey (initial capital cost = $866.1 x 10^6), and the National Commission on Water Quality (NCWQ) study (initial capital cost of $329.6 x 10^6). (18,19) The NCWQ study was the only other one which explains its methodology and assumptions. Thus, a comparison with that study has been made. Major differences in results are attributable to the following:

1. Collection System Costs - The NCWQ estimate includes $84.0 x 10^6 for constructing storm sewers. This study does not view storm sewers as chargeable to pollution control.

2. Choice of a Design Storm - The NCWQ studies used control of the two year, one hour storm as a basis for their mean estimate of control costs. The concept of a design storm was not used in this study because it was felt that a continuous characterization in terms of percent

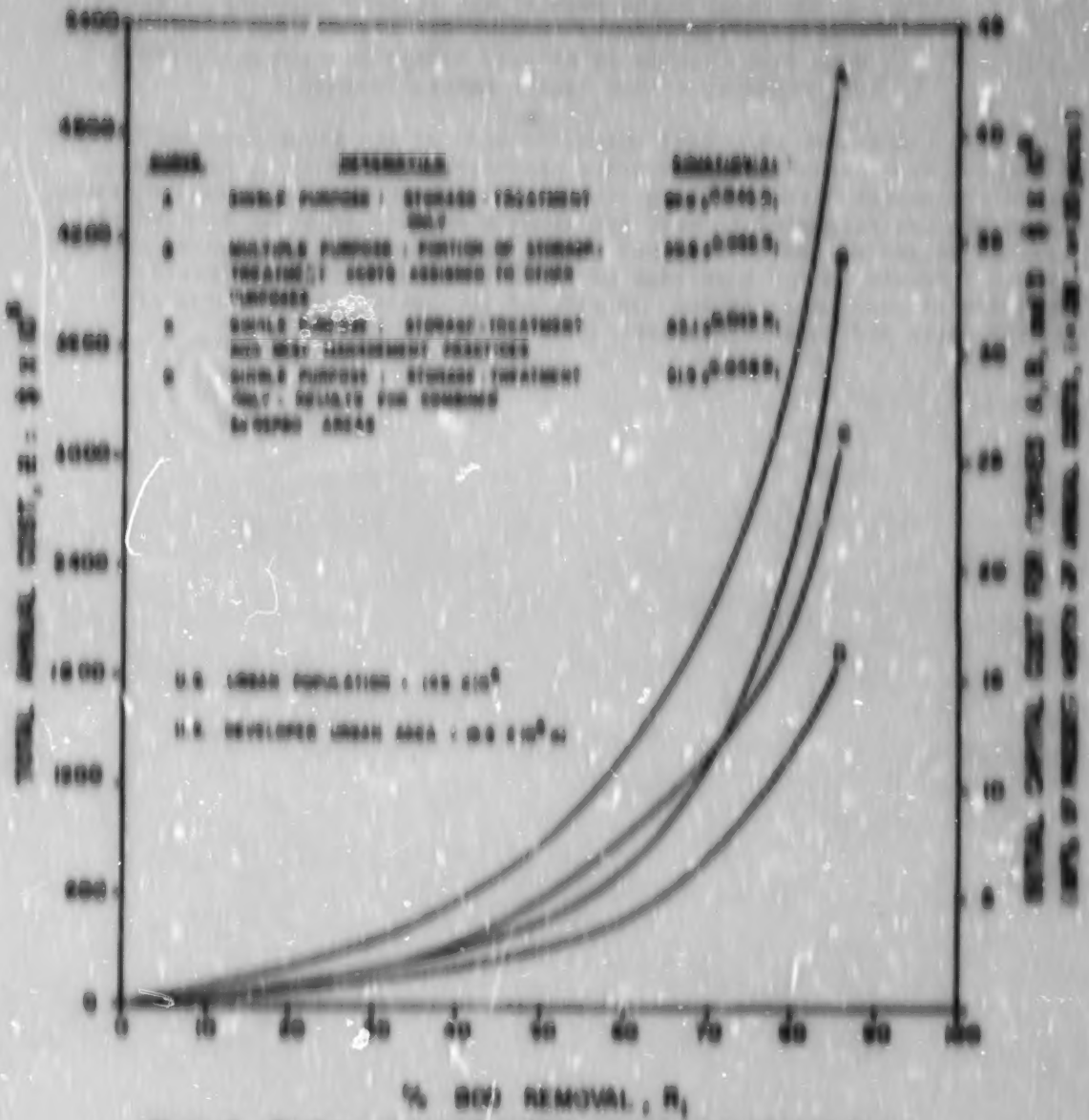

Figure 8. Single purpose and multiple purpose stormwater pollution control costs for U.S.

of the runoff which could be treated was more appropriate since no accepted design event condition exists which also specifies a design antecedent dry-weather period. Figure 4 shows that using a frequency of one month would permit capture of 90 percent of the precipitation volume. Sizing for the two year, one hour storm yields relatively little incremental control and requires a much higher control volume.

Only the future will tell which, if any, of the above cost estimating procedures provides the most accurate estimate of national control costs. Within the severe data gathering limitations imposed by a national estimate, this study has attempted to make the results as site specific as possible. Improved estimates can be obtained using local data. In particular, topographic information and knowledge of the numbers of outfalls permits inclusion of pumping costs and analysis of the optimal combination of control units and interceptor sewers.

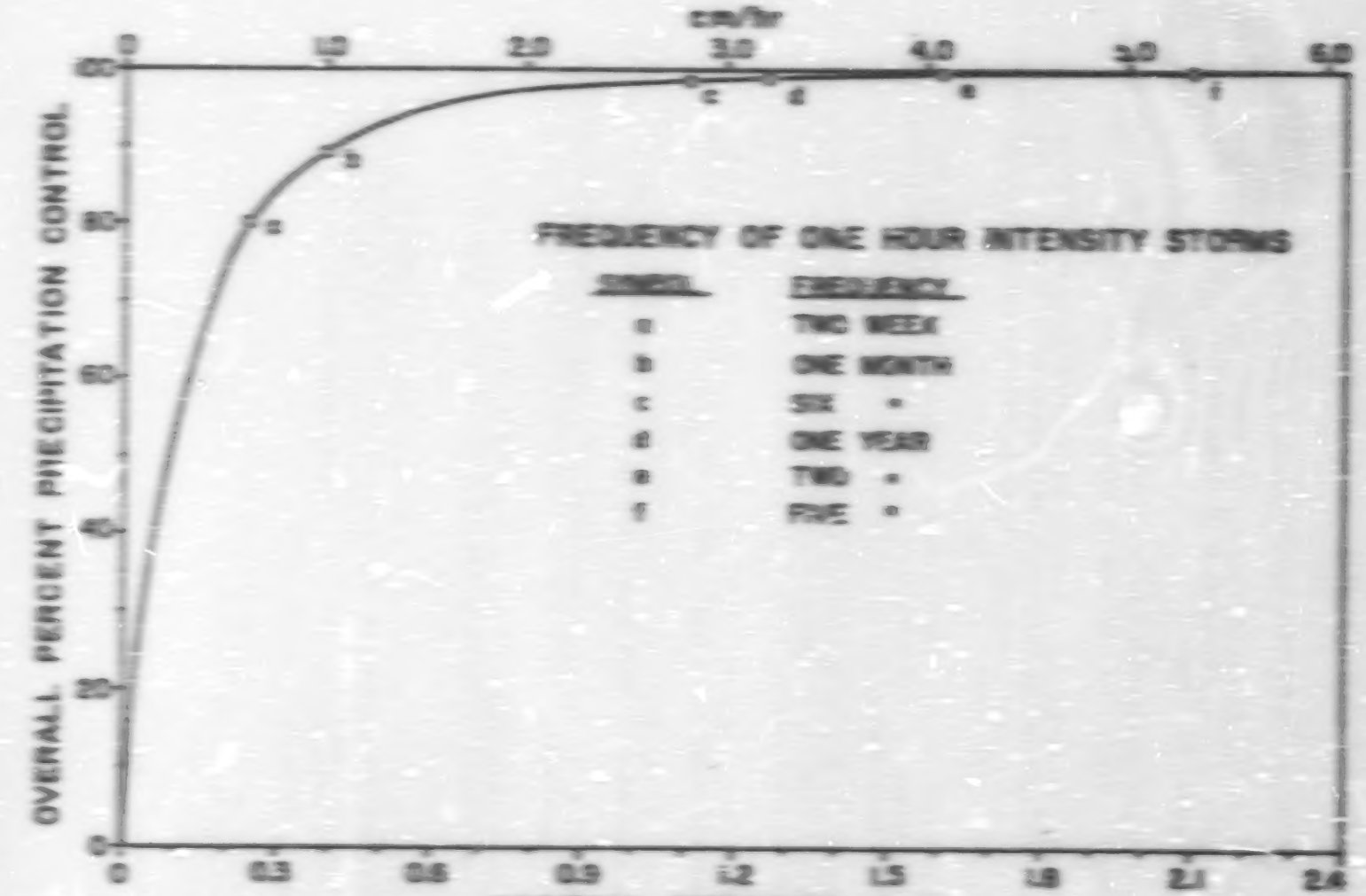

Figure 4. Overall percent precipitation control vs. rainfall intensity – Atlanta, Georgia (1963-1972)

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LIST OF VARIABLES

a	coefficient (inches per hour)
AR	annual runoff (inches per year)
a	coefficient
b	coefficient (inches per hour)
β	coefficient
c_s	unit cost of storage (annual dollars per acre-inch)
c_y	unit cost of treatment (annual dollars per inch per hour)
GR	gross runoff coefficient
GR'	net runoff coefficient
d	coefficient (inch $^{-1}$)
DS	depression storage (inches)
DWF	annual dry weather flow (inches per year)
ENR	Engineering News Record Cost Index
η	treatment plant efficiency
f	coefficient (percent R^{-1})
G_L	curb length (feet per acre)
k	street sweeping effectiveness factor
h	coefficient
I	percent imperviousness
K	coefficient
l	coefficient
M	annual pounds of pollutant (pounds per year)
MRS_{st}	marginal rate of substitution of storage for treatment (hours)
n	annual pounds of pollutant (pounds per year)
N_s	street sweeping interval

P	annual precipitation (inches)
PD	gross population density
PD_d	gross population density in developed portion of urban area
R	percent runoff control
R_1	percent pollutant control
R_1^*	optimal percent pollutant control prior to using tertiary treatment
S	storage volume (inches)
S^*	optimal storage volume (inches)
T	treatment rate (inches per hour)
T^*	optimal treatment rate (inches per hour)
T_1	treatment rate at which isoquant is parallel to the ordinate (inches per hour)
T_2	treatment rate at which isoquant intersects the abscissa (inches per hour)

SECTION III

RECEIVING WATER IMPACT - A CASE STUDY

GENERAL DESCRIPTION

The City of Des Moines, Iowa, is located near the confluence of the Des Moines River and the Raccoon River as shown in Figure 9. It contains approximately 200,000 people out of the total of 286,000 for the metropolitan area.(1) The mean annual precipitation is 31.37 in. (79.5 cm), approximately equal to the United States average. Annual pollutant unit loads upstream from the city were determined (see Table 19).

TABLE 19. POLLUTANT UNIT LOADS FOR DRAINAGE AREA (on annual basis) ABOVE DES MOINES, IOWA (Davis and Borchardt, 1974)[1]

	Des Moines River	Raccoon River	Total
Drainage Area, acres (ha)	3,738,000 (1,513,749)	2,202,000 (891,149)	5,940,000 (2,405,918)
Unit Average Annual Runoff, acre-ft/acre (ha-m/ha)	0.42 (0.13)	0.40 (0.12)	0.41 (0.13)
Unit BOD, lbs/acre (kg/ha)	13.40 (15.02)	6.91 (7.77)	11.01 (12.34)
Unit NO_3, lbs/acre (kg/ha)	5.75 (6.30)	5.76 (6.19)	3.75 (4.20)
Unit PO_4, lbs/acre (kg/ha)	0.56 (0.61)	0.52 (0.67)	0.50 (0.56)

The estimated annual loading from the urban area's 45,000 acres (18,220 ha) of separate sewer and 4,000 acre (1,620 ha) combined sewer systems is shown in Table 20.

Taking the total upstream drainage area for the Raccoon and Des Moines Rivers, the annual pollutant contributions are: 65,223,000 lbs of BOD (29,586,000 kg); 33,331,000 lbs of NO_3 (10,080,000 kg); and 2,940,000 lbs of PO_4 (1,334,000 kg).

Figure 5. Map of Des Moines Area
(Davis and Borchardt, 1974) (1)

| | | |

| | | |

The urban area loadings (when added to upstream values) represent, respectively: 15 percent, 9 percent, and 51 percent of the total BOD, NO_3, and PO_4 mass loadings to the Des Moines River below the metropolitan area. The Davis and Borchardt report estimates made from river sampling data taken below Des Moines indicate the following average annual river loadings: 70,000,000 lbs of BOD (31,751,565 kg); 25,600,000 lbs of NO_3 (11,521,270 kg); and 7,950,000 lb of PO_4 (3,606,059 kg). These figures reveal that: (1) 6,610,000 lbs of BOD (2,998,246 kg) are "lost" in transit through the urban section of the stream, and (2) by contrast 2,474,960 lbs of NO_3 (1,122,391 kg) and 1,917,400 lbs of PO_4 (869,817 kg) are gained in addition to the measured urban sources.

Davis and Borchardt offer some explanations:(1)

> The "sometimes" decrease in organic load through the metro area may be attributable to treatment realized in the low head impoundments at Scott and Center Streets on the Des Moines River and just below Fleur Drive on the Raccoon. To some extent these impoundments may be serving as intermittent sedimentation and stabilization units.
>
> All BOD data, including that used from the two other studies, were obtained from unfiltered samples. However, since the analytical technique was the same for all samples, the relative magnitude of the data should not be affected.
>
> There has been some speculation that treated wastewater effluents may exert an antagonistic or retardent effect on the BOD exertion rate of the receiving stream. If true, this may be due to surfactants or to the expected lower exertion rate of the effluent. In this regard, the decreased BOD_5 in 4 or 5 measurements between R-8 and R-6 is of interest. Increased loads between the summation of R-4 and R-9 versus R-5 are likely due to raw and combined sewage bypassing the intervening area.
>
> Another, and probably the most practical, possibility for discrepancies is the fact that the data are biological and biochemical in nature and such data do not always provide predictable conservative summations.

The sampling stations (numbers 4, 5, 6, 9) are shown in Figure 6. Intervening creeks, such as Beaver Creek, which carries nutrient loads of 2,860,000 lbs of NO_3 per year (1,297,274 kg per year) and 190,000 lbs of PO_4 per year (175,900 kg per year), may be an answer to observed differences in the nitrate loads. However, the phosphate totals are still unbalanced and the cause unresolved.

Figure 8. Location map: river sampling points (Davis and Borcherdt, 1974)

DATA AND MODELING

The data may be broken into categories describing needs for the runoff simulation. All land use, population density, areas, curb lengths, etc., were obtained from data prepared by AFNA for STORM simulations (Volume III). Hourly rainfall values for the year 1968 were obtained from the National Weather Records Center at Asheville, North Carolina. The area served by combined sewers A_s = 4,000 ac, is given on p. 9 of the Davis and Borchardt report. (1) Dry-weather flow values are taken from Table 5, p. 51. Receiving water upstream flows, temperatures, BOD and DO levels are taken from pp. 285-306. Total urban runoff and its BOD concentration are obtained from the STORM simulation on a hourly basis.

Stream DO's were simulated using a Streeter-Phelps formulation. More sophisticated procedures were not warranted due to a lack of supplemental data required for such models. Measured and computed values of DO at a point 5.6 mi (9.0 km) downstream from the confluence of the Raccoon and Des Moines Rivers are compared in Figure 7. Correlation between the calculated and observed profiles is quite good. The point corresponds to sampling location No. 8 as shown previously in Figure 6. Included in Figure 7 are rainfall and average total river flow values for each wet-weather event. Differences between measured and computed DO concentrations may be attributed to such factors as: (1) the time of day during which the sample was taken; (2) a lack of data on photosynthesis, algal respiration, and benthic demand. The time scale in days represents the wet year beginning on March 8 and ending December 30, 1968. Again, it should be reemphasized that these DO values are not the minimum DO's resulting from maximum deficits. The maximum deficits occur much further downstream (10-30 mi or 16-48 km) and water quality standards are violated much more frequently.

RESULTS

Based on NOAA records (Asheville, North Carolina), the total precipitation that fell over the Raccoon, Iowa, during 1968 was 37.59 in. (76.1 cm). STORM computed a total runoff of 10.28 in. (26.1 cm) over a watershed area of 49,000 acres (19,500 ha), for an overall urban area runoff coefficient of 0.37. There were 65 days in the year during which rainfall was recorded, from which 58 wet-weather events were defined. The results are presented in the form of minimum DO frequency curves for the wet-weather and dry-weather periods through the calendar year.

Figure 8, illustrates all waste inflow combinations. The curves indicate clearly that all combinations including a substantial amount of wet-weather flow (WWF) result in a drastic decrease in river minimum DO concentrations. For example, 40 percent of all the wet-weather events throughout the year produced conditions in the receiving water that caused minimum DO levels below 4.0 mg/l. Combined sewers contributed WWF from only 8 percent of the total urban area modeled, yet the BOD_5 concentration was sufficiently high to inflict an appreciable reduction in DO levels when compared to WWF sources during periods of runoff.

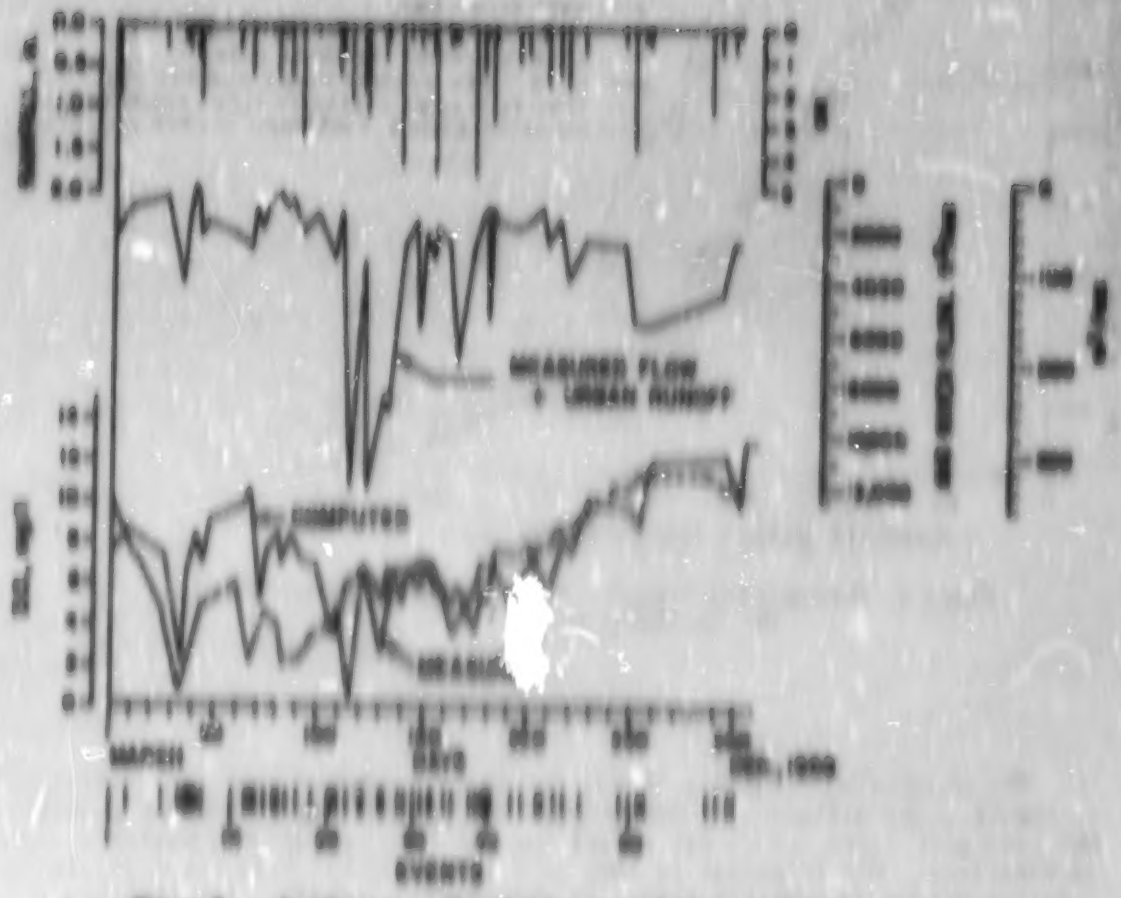

Figure 7. Application to Des Moines, Iowa. Measured and computed values of Q(t) at S.R. no. 163 (km) downstream from confluence of Raccoon and Des Moines Rivers.

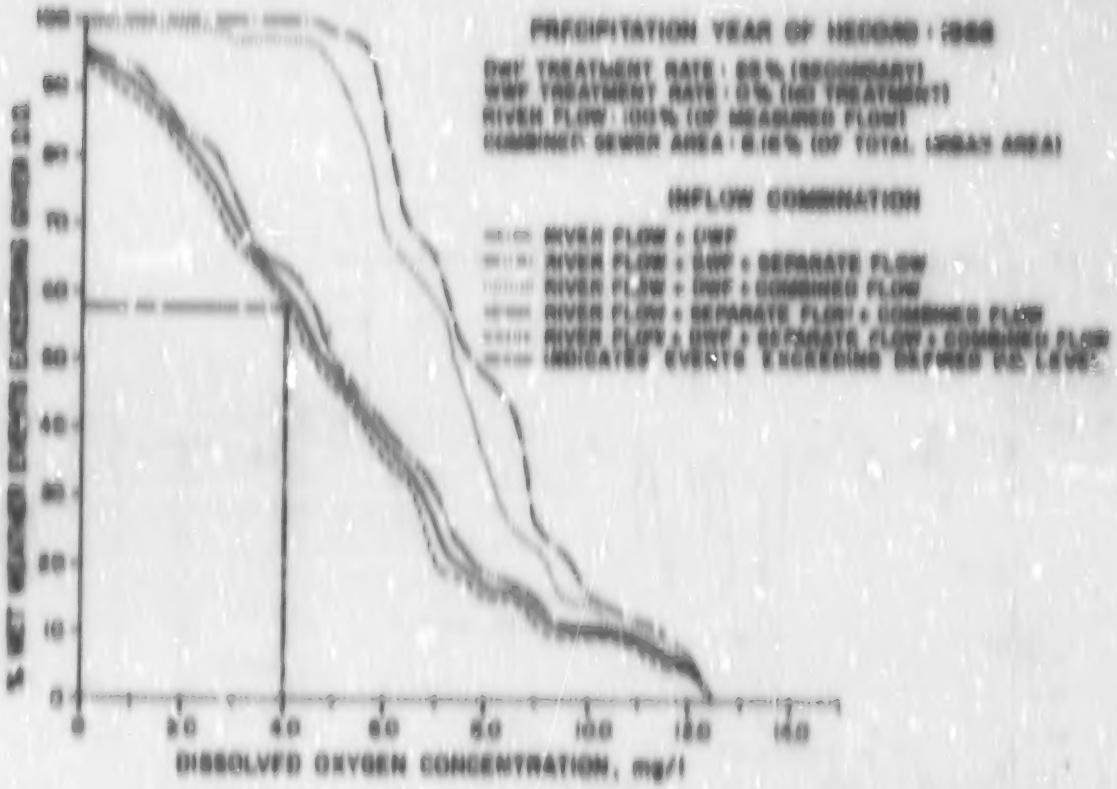

Figure 9. Minimum DO frequency curves for existing conditions in the Des Moines River

The minimum DO frequency curves in Figure 9 compare four alternatives to reduce water pollution during wet-weather periods, plus zero and primary DWF treatment curves shown for comparison but not considered acceptable alternatives. WWF treatment is seen to be considerably more effective in reducing stream DO violations than is secondary or tertiary DWF treatment. In fact, results indicate that a DO standard of 4.0 mg/l would be violated only three percent of the time during wet weather if 75 percent WWF treatment were instigated.

It is now appropriate to examine the results of applying the model to periods throughout the year during which no urban runoff was produced. Dry weather was experienced for approximately 300 days throughout 1968. The model was applied to these periods using a daily time step. This modification is certainly justified since conditions are more truly steady-state than during periods of precipitation and subsequent runoff. For example, waste loadings (DWF treatment plant effluent) and river flow do not vary as much during the day. For the dry-weather simulation period, upstream river flow was on the average 94 percent of the total river flow, ranging from 88 percent to 99.6 percent. The results are shown in Figure 10. A remarkable 97 percent of the dry-weather days exceed a minimum DO concentration of 4.0 mg/l.

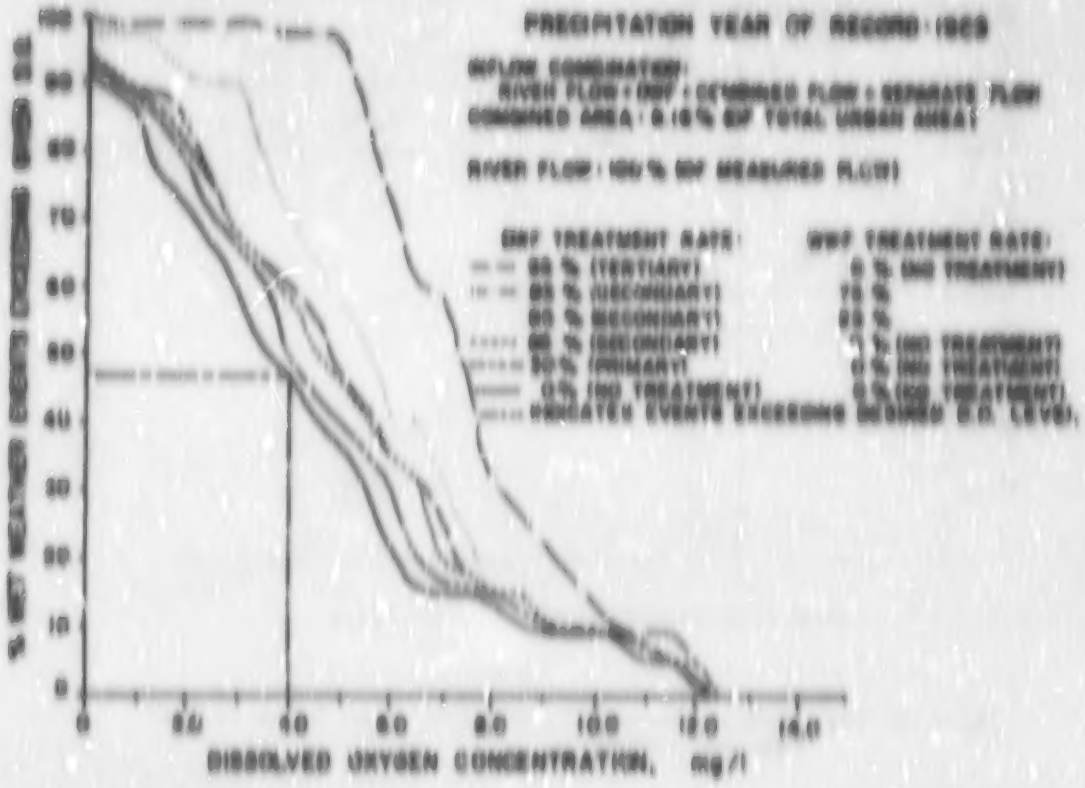

Figure 9. Minimum DO frequency curves for varied treatment alternatives

Upgrading of DWF treatment becomes meaningful only if stream DO standards are set higher than 4.0 mg/l. From Table 19 it is clear that the Des Moines River in particular carries a high BOD_5 load upstream of the Des Moines urban area. This explains why, even during dry-weather periods only, a significant increase in the DWF treatment rate does not result in a corresponding increase in the critical DO levels, as shown in Figure 10.

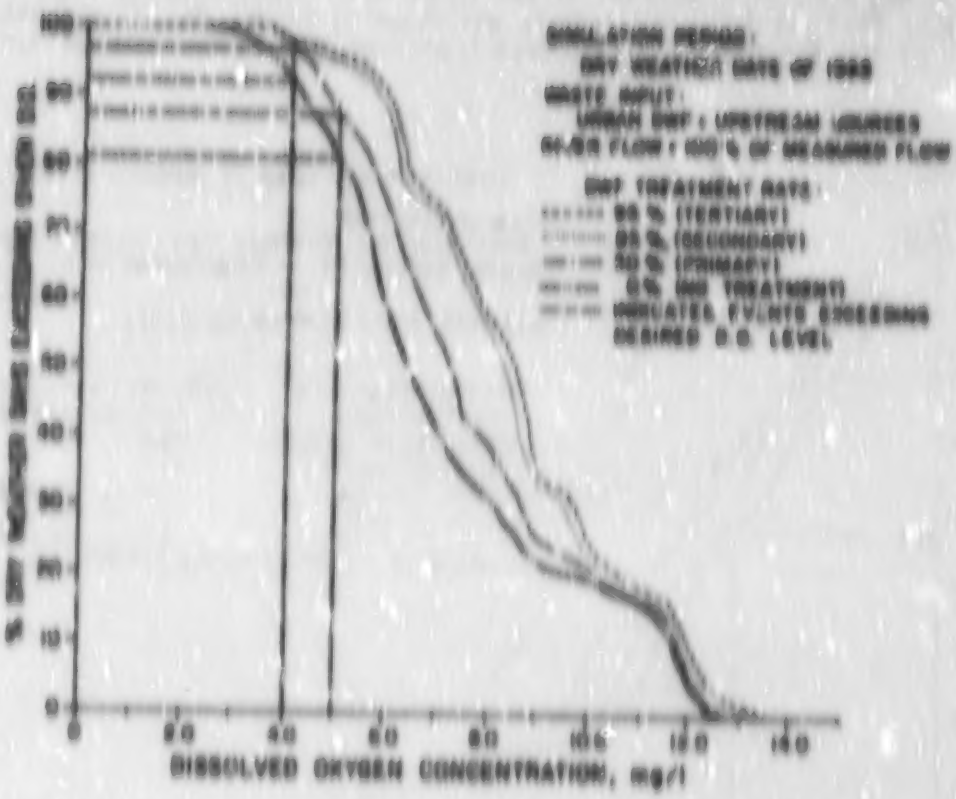

Figure 10. Dry-weather minimum DO frequency curves for varied DWF treatment alternatives

To maintain the proper perspective, it is desirable to view the effects of urban runoff on an annual basis, not just during periods of wet-weather. The frequency curves shown in Figures 9 and 10 are combined by weighting on the basis of the number of rainfall days and dry-weather days in the year.

The composite totals are presented in Figure 11. For example, a given stream standard of 4.0 mg/l is exceeded 90 percent of the time for existing conditions in Des Moines, Iowa, throughout the year 1968. A significant amount of treatment (75% BOD5 removal) of WWF in addition to secondary treatment of DWF results in critical DO levels such that the same stream standard is exceeded 97 percent of the days in the year. Annual DO duration curves tend to mask the impact of shock loads of organic pollutants discharged during periods of urban runoff. A few extended violations of stream DO standards may cause anaerobic conditions resulting in fish kills and proliferation of undesirable microorganisms.

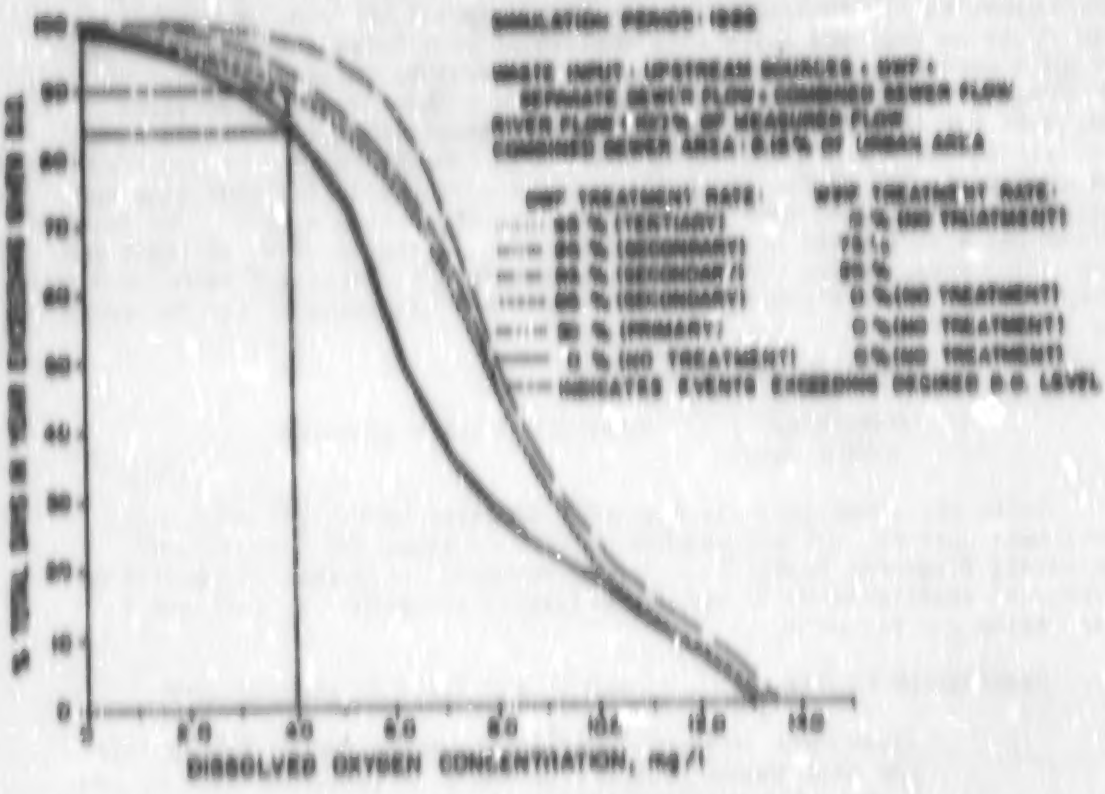

Figure 11. Annual minimum DO frequency curves

TRADEOFF IN ALTERNATIVES

To view the control strategies in the proper perspective, the status quo conditions are included as a base for comparisons. Any alternative alone that report from this base must be justified on their cost-effectiveness. Thus, the cost figures shown in Table 11 represent the additional expense incurred in providing [illegible] above those treatments available with secondary treatment at DMP and no control of urban runoff. Figures 9, 10 and 11 show the effects of various control strategies upon the minimum DO concentrations of the Des Moines River.

The Des Moines River stretches for 200 mi. (322 km) from the City of Des Moines to its junction with the Mississippi River and, in general, the river is wide and swift with occasional deep holes and a broad flood plain. According to the State Hygienic Laboratory, bottom material is composed of silt deposits, sand, gravel and rubble providing numerous habitats for fish and other aquatic life. Recreational activities such as fishing and boating are quite heavy. The entire reach is classified as warm water "B" stream by the Iowa Quality Standards (2) such that the absolute minimum dissolved oxygen level specified is 4.0 mg/l. The Iowa Standards also require a minimum of 5.0 mg/l during at least 16 hours per day. (3) Thus, taking 4.0 mg/l as the standard or basis for water quality comparisons, the different control options may be judged by the following criteria:

1. total annual cost, and

2. violations of the minimum allowable dissolved oxygen level.

Table 13, summarizes the cost-effectiveness of two advanced waste treatment options, two wet-weather control options, and existing DMP secondary treatment facilities. For comparative purposes, two additional treatment conditions which are not presently acceptable by government regulation are presented.

Examination of Figures 9, 10 and 11 and Table 13 reveals that:

1. Since both types of tertiary treatment remove essentially the same amount of BOD$_5$, option 1 is justified over option 2 only when nutrient removal is necessary;

2. option 4 is preferred over any form of advanced waste treatment;

3. option 3 is attractive because it causes the least amount of damage to the receiving stream, but it is the most expensive alternative; and

4. any reduction in the degree of DMP treatment for existing conditions, option 5, results in a substantial deterioration to receiving water dissolved oxygen levels and must be weighed against the savings incurred.

| | | |

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]

Again, the issue of shock loads is important and favors high levels of WWF control.

The reader should be cautioned that advanced tertiary treatment is rarely imposed just to improve the BOD removal capabilities of existing facilities. It is usually designed specifically for nitrogen and/or phosphorus removal. For the heavy precipitation in the months of June, July and August, 1968, Davis and Borchardt (1) reported the following nutrient concentrations at a point approximately 5.5 mi (9.0 km) downstream from the confluence of the Raccoon and Des Moines Rivers:

1. total organic nitrogen ranged from 1.6 to 3.7 mg/l,

2. nitrate nitrogen ranged from 0.2 to 7.0 mg/l, averaging 3 to 4 mg/l, and

3. orthophosphate (OPO_4) ranged from 0.6 to 1.8 mg/l, averaging slightly over 1.0 mg/l.

Since most of the urban runoff would overflow untreated to the receiving water, any program of advanced treatment given to all urban WWF would be relatively ineffective. It would also be questionable whether a level of WWF control consisting of secondary treatment (such as that evaluated for 75 percent BOD removal) could reduce nutrient levels in the Des Moines River and Red Rock Reservoir to inhibit aquatic plant growth. Davis and Borchardt (1) observed high algal densities in both the Des Moines and Raccoon Rivers, and they also state that nutrient concentrations are almost always present at levels reported by Sawyer (8) to be sufficient for nuisance algal growths: 0.3 mg/l for inorganic nitrogen (NH_3, NO_2, NO_3) and 0.015 mg/l of inorganic phosphorus. Furthermore, since nitrates are abundant in groundwater and the surface and subsurface hydrologic systems are not independent of each other, nutrient control seems highly complex and improbable.(9)

The total annual precipitation for the year 1968 was 27.99 in. (70.1 cm). The frequency and intensity of precipitation over an urban area has a direct bearing on the magnitude of stormwater pollution and, consequently, dissolved oxygen levels in the receiving water. In the selection of the "best" control strategy, other factors may become important, such as:

1. recovery of receiving waters from shock loads during runoff periods,

2. local and regional water quality goals,

3. public willingness to pay the costs associated with each level of control, and

4. consideration of alternate use of WWF facilities as DWF treatment facilities during periods of no urban runoff.

In general, although selection of a storage/treatment configuration involves many factors it is important to note that the impact of urban stormwater runoff must be evaluated. Davis and Borchardt[1] compared daily pollutant loadings (BOD, SS, PO_4) from storms ranging in size from 0.175 in. (4.4 mm) to 8 in. (192.0 mm) in total depth to those from dry-weather sources in the Des Moines metropolitan area. In all cases, the loads derived from urban runoff exceeded greatly the average daily loads from dry-weather sources.

REFERENCES

1. Davis, P. L. and Borchardt, F., "Combined Sewer Overflow Abatement Plan," USEPA Report EPA-R2-73-170, April 1974.

2. State Hygienic Laboratory, "Des Moines River - Limnology Study," Report submitted to the Department of Environmental Quality and the Iowa Water Quality Commission, April 1974.

3. State Hygienic Laboratory, "Water Quality Survey of the Des Moines River," Report submitted to the Iowa Pollution Control Commission, October 1970.

4. Sawyer, C. N., "Basic Concepts of Eutrophication," JWPCF, Vol. 38, No. 5, pp. 737-741, May 1966.

5. Sawyer, C. N., "The Need for Nutrient Control," JWPCF, Vol. 40, No. 3, pp. 363-370, March 1968.

SECTION IV

URBAN STORMWATER POLLUTANT LOADINGS

Federal interest, legislation and financial support through the research and development programs of the U.S. Environmental Protection Agency (USEPA), has stimulated extensive studies of the nature of urban stormwater runoff and combined sewer overflow pollution over the past 15 years. Financial support by Federal, state, local and private entities has resulted in better understanding the general areas of treatment; sewer system monitoring, regulation and control; runoff and combined sewer overflow characterization; and mathematical modelling for estimating the quantity and quality of runoff and combined sewer overflows. The resulting body of knowledge has produced new technologies with which to estimate, evaluate and analyze the pollutional contributions of urban runoff, as well as effective methods for their abatement and control. The basis of and the major limitations to this technological advancement dictate the methods by which urban runoff quality and quantity are ascertained.

Runoff quantity estimating methods are well defined. Contemporary techniques can produce fairly accurate results within reasonable objectives, based on available data. The major concern is the accuracy of physical and hydrologic data. Physical data may be gathered from existing sources, while monitoring networks are seldom available. Historical hydrologic records, therefore, are a significant data source.

Estimation of runoff quality is not well defined. Quality estimating methods, on one hand, have been based on the characterization of discharge pollution and receiving water monitoring. On the other hand, an alternative approach has been to identify and evaluate potential pollutant sources that may contribute to the deterioration of runoff quality. These varied approaches to the problem of analyzing the quality and pollutional contributions of urban runoff demonstrate that no single best method now exists. Each approach requires verification based on field sampling and laboratory analysis. The diversity of these approaches, however, is desirable. In total they implicitly suggest both structural and non-structural responses to the problem of the prevention, control and abatement of the pollutional contributions associated with urban runoff. Thus, with further research and evaluation and with the reconciliation of the results attributable to each, solutions to the problems of runoff pollution may be sought in cost-effective alternatives other than wastewater treatment hardware. Some of these alternatives may take the form of solutions as mundane as; improved street cleaning technologies; building code revisions, revised physical development standards; new paving materials; and revised street construction standards.

ALTERNATIVE APPROACHES TO QUALITY CHARACTERIZATION OF RUNOFF DISCHARGES

The quality characterization of runoff discharges has been attempted through various sampling and measurement activities in drainage basins across the country. These basins have often been urban or urbanizing. On occasion, relationships between discharge quantity and quality data have been related to physical basin characteristics and given rainfall events. Inconsistencies exist within this body of information, however, due to variability in the research objectives to be met, the pollutants being evaluated, the sampling techniques employed, and the measurements made.

A number of published references were reviewed to determine the extent and adequacy of existing data sources. Approximately 18 sites were identified where surface runoff quality data in some form were available. Of these, only six provided any definition of drainage basin characteristics as to land use, population or development characteristics. Sampling activities were found to vary considerably. Composite samples were collected most often by automatic devices and grab techniques. Related flow measurements were made in only a few instances. Similarly, flow-related discrete sample collection occurred at only one location, although discrete grab samples were used often in conjunction with automatically collected composite samples. Sampling site location also plays an important role in defining sampling results. As an example, it is likely that combined sewer sampling occurs most often within or at the discharge of a sewer collection system. Similarly, separate system sampling may occur at locations within the system or at the point of discharge into receiving waters. Very often, separate storm systems may take the form of open earthen channels, in whole or in part. Sampling at these locations adds solids components and other pollutants during a meaningful runoff event due to gully and channel erosion and other conditions. This would not be experienced to the same degree in a combined sewer system. Thus, most of the existing runoff discharge quality information appears in the form of mean pollutant concentrations or averages of sample results from one or more runoff events, most often without regard to rainfall-runoff relationships and other variations in time.

Discharge quality and time and runoff flow data have been published in only a few locales. Foremost among these is a published study from Durham, North Carolina(9) that investigated a separate storm runoff collection system in terms of the quality of surface runoff with respect to runoff quantity during a number of rainfall events. An analysis of the collected data disclosed that the discharge rate and the time from the beginning of the storm event were the most significant factors in defining variations in pollutant concentrations during periods of runoff. These concentrations were generally found to increase with increasing discharge and to diminish with increasing time after the beginning of the storm event. Antecedent dry days -- days from the time of the preceding rainfall-runoff event -- were not found to be a significant factor in the quality of the runoff sampled. These findings indicate the existence of a "first flush" or the removal of pollutant deposits within the collection system by the initial runoff flows. The "first flush" is generally characterized as having high initial pollutant concentrations that diminish with time. It should be noted that the "first flush"

reflected in the Durham study was one that occurred in a collection system primarily composed of open earthen channels and not in a combined sewer system.

Currently available discharge data leave much to be desired. The original objectives for the majority of the information available were to produce order-of-magnitude estimates of the pollution represented by runoff discharges. This type of information, once having fulfilled its basic purposes, is no longer timely. Thus, further research in this area is indicated.

POTENTIAL POLLUTION SOURCES

The evaluation of potential pollutant sources originated primarily in the study of non-urban environments and non-point runoff discharges. Generalizations from this body of knowledge are now being applied to urban drainage areas to estimate pervious area pollutional contributions. The use of the so-called Universal Soil Loss Equation (USLE) for the estimation of sediment contributions is a good example of non-urban technology in use in urban applications. Other, more specifically urban pollutional sources, require further research and evaluation. It is apparent that the products of combustion and other suspended materials in the air -- particulates and other emissions -- may be scavenged from the atmosphere by falling rain. Depositions of airborne materials on pervious and impervious surfaces may be washed off by runoff. Other materials may also contaminate runoff. Street paving and surfacing materials; debris from open areas, including wind and water erosion products, organic, plant and animal wastes and a variety of chemicals such as fertilizers, soil conditioners and pesticides; transportation-related materials, including residual deposits of fuel, lubricants, hydraulic fluids and coolants, tire, clutch and brake-wear products, exhaust emissions particulates, rust and dirt; street litter, household and commercial wastes; and snow and ice control, antiskid and corrosion inhibitor materials -- all may contribute to runoff contamination. In addition, the stored contributions of catch basin and collection system solids depositions may be added to this list.

One of the major urban sources of potential pollution is related to transportation activities. A recent study of the pollutants generated by vehicular traffic was carried out in Washington, D.C. (1). This study involved the collection of street accumulation samples and of traffic volumes during sampling periods. Analysis of the results of street measurements compared with traffic volumes produced the accumulation rates shown in Table 23. Although these values appear relatively low, they are of considerable significance when applied to high traffic volumes.

Snow and ice control activities represent another prospective source of potential pollution. On one hand, snow and ice deposits are a repository of potential pollutants produced in urban areas. The concentrations of various pollutants found in urban snow sampled in the Ottawa-Carleton area of Ontario, Canada, are summarized in Table 24.

TABLE 55. ACCUMULATION RATES OF TRAFFIC INFLUENCED ROADWAY MATERIALS

Washington, D.C. Metropolitan Area

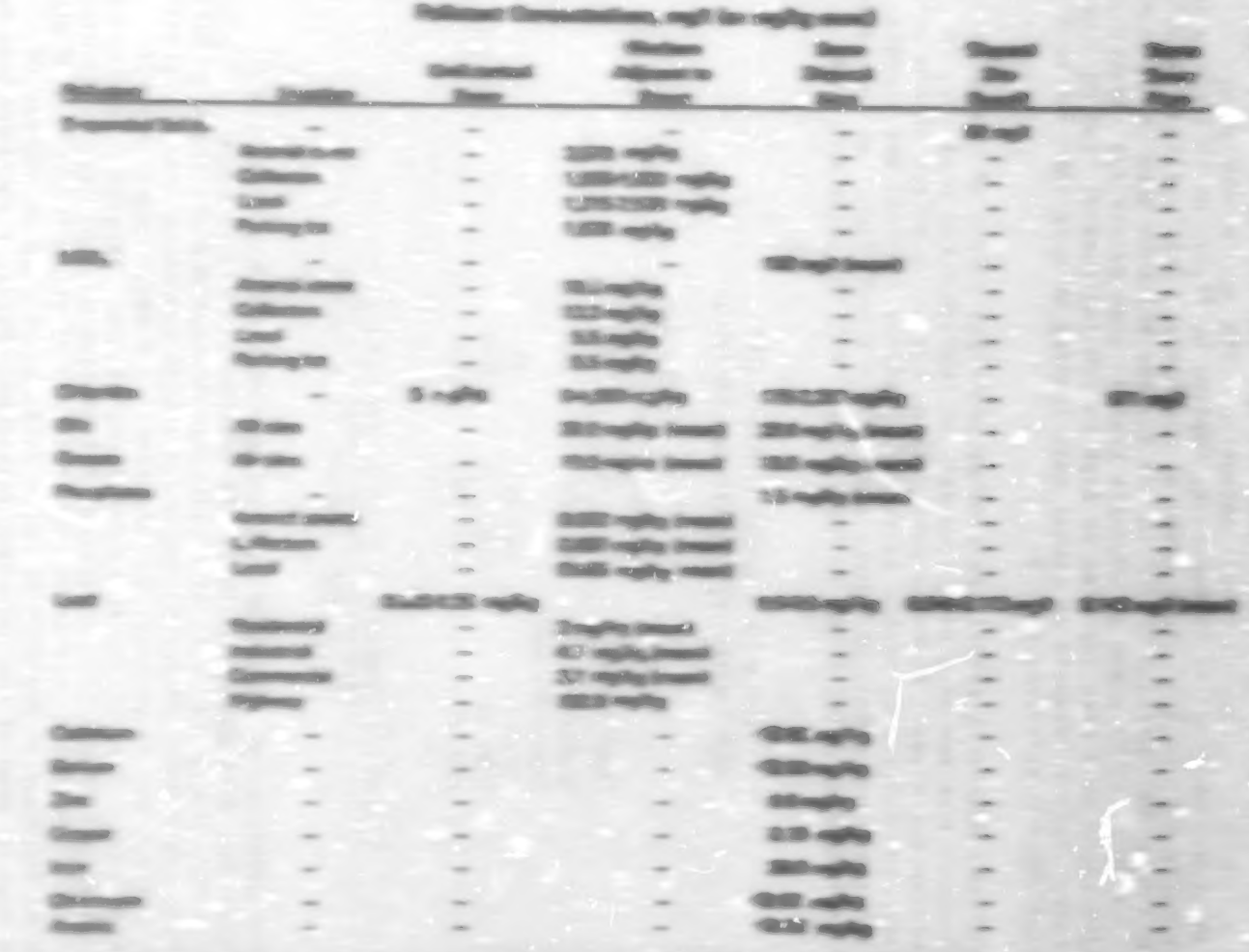
Parameter	Rate lb/acre-yr	Rate g/m²-yr
Dry Weight	2.36×10^{5}	2.71×10^{4}
Volatile Solids	1.21×10^{4}	3.41×10^{3}
BOD	6.43×10^{3}	1.83×10^{3}
COD	1.28×10^{4}	3.61×10^{3}
Grease	1.62×10^{3}	4.28×10^{2}
Total Phosphate-P	1.44×10^{3}	4.05×10^{1}
Orthophosphate-P	4.31×10^{3}	1.21×10^{3}
Nitrate-N	1.40×10^{2}	3.93×10^{3}
Nitrite-N	3.26×10^{3}	9.17×10^{4}
Kjeldahl-N	5.72×10^{2}	1.60×10^{2}
Chloride	2.20×10^{2}	6.2×10^{2}
Petroleum	9.42×10^{3}	2.4×10^{3}
n Paraffins	6.69×10^{3}	1.88×10^{3}
Asbestos	3.86×10^{3} [a]	2.39×10^{4} [a]
Rubber	1.24×10^{3}	3.48×10^{4}
Lead	2.75×10^{3}	7.69×10^{4}
Chromium	1.86×10^{3}	5.21×10^{4}
Copper	2.84×10^{3}	8.00×10^{4}
Nickel	4.40×10^{3}	1.24×10^{3}
Zinc	2.80×10^{2}	8.38×10^{3}
Cadmium	3.11×10^{4}	8.76×10^{4}
Magnetic Fraction	1.26×10^{2}	3.55×10^{3}
Polychlorinated Biphenyls	1×10^{4}	2.82×10^{10}
Litter dry weight	1.69×10^{2}	4.76×10^{3}
Litter BOD	3.49×10^{3}	9.84×10^{4}

a. In fiberglass.

Note: An axle mile is the length required for each axle of a vehicle. Hence in traveling one mile, a two axle vehicle and semitrailer has axle miles.

Source: Shaheen, D.G., "Contributions of Urban Roadway Usage to Water Pollution," USEPA Report No. [illegible] (NTIS No. PB 240 689), April, 1975.

TABLE 24. POLLUTANTS AND POLLUTANT LEVELS FOUND IN SNOW SAMPLES



On the other hand, procedures used for snow and ice control may also create a source of potential runoff pollution. The most commonly used deicing agent now employed is common salt, applied by itself or in combination with abrasive materials or other chemical additives. Salt application rates of from 300 to 500 lbs/lane-mi (85 to 140 kg/lane-km) have been recommended for ice at 10°F (-3°C) where an adequate traffic load exists (3). However, application rates have been reported as high as 700 lbs/lane-mi (196 kg/lane-km) in Toronto. This represents an annual salt loading of more than 180 tons/street-mi (90,400 kg/street-km) (3).

Airborne materials constitute another potential source of contaminants. These contaminants may originate naturally or through human activity, as particulates and gases. Airborne particulates may be deposited within an urban area for subsequent pickup in runoff. Rain or snowfall may scrub airborne materials and gases, and carry them into a runoff flow. An indication of the contaminants level found in rainfall in Cincinnati is shown in Table 25.

TABLE 25. CONCENTRATION OF CONTAMINANTS FOUND IN RAINFALL

Contaminant	Range During Storm (mg/l)	Average Storm Concentration (mg/l)
Suspended Solids	0.5 – 68	13.0
Volatile Suspended Solids	0.5 – 12	3.8
Inorganic N	0.15 – 2.5	0.88
Ortho PO_4	0 – 0.9	0.34

Source: Weibel, S.R., et al., "Urban Land Runoff as a Factor in Stream Pollution," Journal - Water Pollution Control Federation, Vol. 36, No. 7, July, 1964.

The magnitude of deposited particulates on a monthly basis can be determined for data collected in 77 mid-western cities, as shown in Figure 12. The hypothetical effects of particulate depositions are shown in Table 26. This table shows projected suspended solids concentrations for runoffs of 100 percent and 33 percent, in comparison to measured surface runoff concentrations. Some of the heavy metal constituents reflected in dustfall are tabulated in Table 27. Additional information on particulate emissions is available through the publications of the USEPA Office of Air and Water Programs at Research Triangle Park, as well as in reports of recent work on some of the non-point emissions. Nutrient contributions may also be attributed to airborne sources. Nitrogen compounds exist in the atmosphere and are removed in bulk precipitation. (4) Similarly, phosphorous precipitation, although typically small, can be cause for concern where receiving waters may be subject to eutrophication. (5) Phosphorous precipitation rates have been reported in the range of from 0.015 to 0.76 grams

TABLE 26. COMPARISON OF SUSPENDED SOLIDS CONCENTRATIONS COMPUTED FROM DUSTFALL AND MEASURED VALUES

(Rainfalls are mean values from two stations adjacent to study area)

	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.
Mean Rainfall (tons/mi²/mo)	7.1	4.9	4.6	6.7	1.9	5.4	5.6
(g/m²/mo)	8.0	1.79	1.70	2.56	1.68	2.04	2.16
Monthly Rainfall (in)	4.3	3.6	3.6	7.0	6.2	4.6	4.6
(mm)	109	86	91	184	158	117	117
Calculated Mean Solids Concentration (mg/l)							
100% runoff	23	14	15	13	12	20	21
50% runoff	46	41	43	37	24	40	42
Measured Mean Surface Runoff Suspended Solids (mg/l)							
Lakewood Rd.		147		131		104	
Cambridge St.		191		84		80	

Source: Holtz, R.D., "Airborne Contribution to Surface Run-off and Sediment from Dustfall Particles in an Urban Watershed", Water Resources and Hydraulic Engineering, Report, Tulane, April 1971.

per square meter per year. (6). These values may be found to be considerably higher in urban areas due to industrialization and urbanization. (7)

TABLE 27. GEOMETRIC MEANS FOR CADMIUM AND ZINC FOR 21 MIDWESTERN CITIES
kg/km²/mo (ton/mi²/mo)

	LAND USE			
Pollutant	Residential	Commercial	Industrial	
Cadmium	0.038 (0.0001)	0.063 (0.00018)	0.071 (0.0002)	
Lead	5.212 (0.015)	19.893 (0.057)	8.700 (0.025)	
Zinc	3.883 (0.011)	4.799 (0.027)	19.519 (0.056)	

Source: Hunt, R.P., et al., "A Study of Trace Element Pollution of Air in 21 Midwestern Cities", Paper Presented at the Fourth Annual Conference on Trace Substances in Environmental Health, University of Missouri, June 1970.

Soil erosion contributions to the problems of water quality are well documented. Sediment is perhaps the largest single source of water pollution. Sediment production varies according to land use and physical site characteristics. Some comparative estimations of relative sediment yield are shown in Figure 13. This figure shows findings for areas of differing slope and land uses in the Central Atlantic States. It also shows the high yields found in conjunction with exposed or uncovered sites. Sediments represent pollutional contributions in the form of solids, organic loadings and their related oxygen demands, nutrients, acid salts, trace metals, and various other chemicals such as pesticides and herbicides. Estimating functions for nutrient losses by erosion processes have been proposed by Midwest Research Institute. (8)

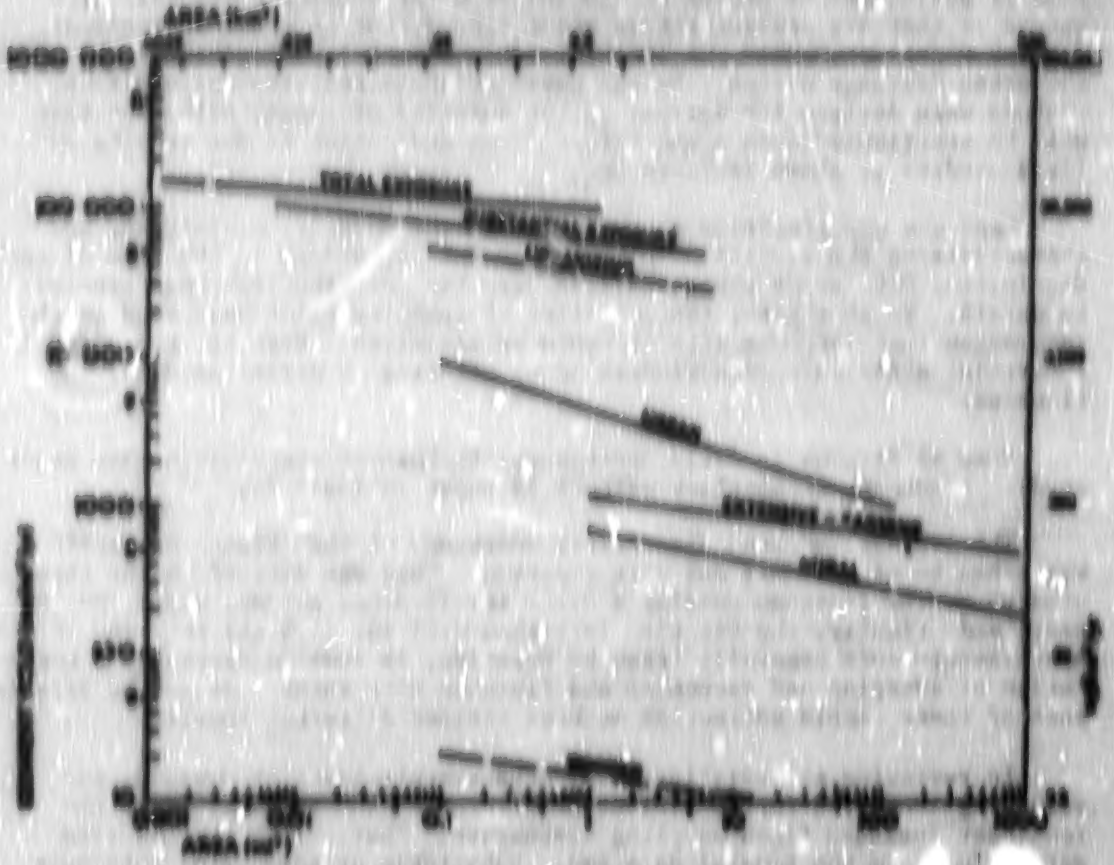


Figure 13. Sediment yield vs contributory basin area

Source: Wilson, L.G. and E.A. Cochrane, "Urban Studies at a Scale of Priority," Paper prepared for the Twenty-Fifth Annual Water Resources and Pollution Control Conference, Chicago, Ill., March, April, 1971.

It is apparent that research and evaluation related to urban pollutant sources are lacking, although important initiatives involving vehicular contributions as well as those related to street surface accumulations have been taken. Many of the analytical methods employed to estimate source contributions are new; urban in their origins and their applicability for urban areas remains to be verified. Other verifications are needed for average runoff estimating methods that are being applied to newer shorter time intervals. A general deficiency of data exists in a number of the pollutant source areas previously discussed, indicating the need for additional study.

The magnitude of pollutants that may be available for pickup in surface runoff has been assessed. The basic assumption of the approach has been that the developed urban street is a temporary depository for the accumulation of pollutants -- presumably coming from the sources previously discussed -- that are representative waste products of an urban environment. Another major assumption was that the urban street is a logical extension of the urban drainage system. On the basis of these and other assumptions, methods were devised for estimating the quantity of runoff pollution that will be contributed from urban streets. An indication of the results of field loading is shown in Table 18.

Land use was generally acknowledged as the means of classifying and characterizing the results of field measurements, except in the case of the Washington, D.C. study where vehicular traffic contributions were studied in detail. In this case, the selection of sampling sites was based on the assumption that land-use effects could be minimized. Even so, two sites in commercial areas were acknowledged to be affected by strong land-use influences.

Some variations in field measurement techniques occurred in each major study. A summary of sampling methods is shown in Table 19.

The largest and most susceptible component of the effects of runoff was taken to be the dust and dirt fraction. This was defined in the three studies as the fraction passing a 0.125 in. (0.3 cm) screen, a U.S. No. 6 sieve and, finally, the fraction less than 0.15 in. (0.4 cm) in size. Field measurements were generally taken by sweeping, in some instances by a combination of sweeping and vacuuming and flushing with water. As may be expected, each of these sample collection methods yielded different results.

In reviewing all existing data, measurements taken by sweeping and vacuuming accounted for 90 percent of a total of 600 samples, while the remainder included flush sampling components. Thus, flush samples were not included in the general data set. Data taken at known time intervals at the same sampling locations were found to produce coefficients of variation of from 0.4 to 0.6 while the multi-city sampling of initial conditions resulted in coefficients of from 1.0 to 1.8. Thus, it appears that a higher level of replicability was found for samples taken at the same site at know time intervals. In addition, the majority of the data in this set

TABLE 28. COMPARATIVE SUMMARY OF REPORTED VALUES FOR STREET SURFACE SOLIDS ACCUMULATION LOADINGS BY LAND USE
(Dust and Dirt Fraction)

Land Use	APWA[1]	USGS[2] Rossmiller Company 1973	Pitt-Shelley[3] 1975	Sartor[4] Boyd U.S. Corps of Engineers	USGS[5] Rossmiller Company 1974
Residential	---	100 (500)	---	4.01 (19.7)	43 (149)
Single Family	10 (37)	---	---	---	---
Multi Family	34 (121)	---	---	---	---
Commercial	49 (174)	51 (183)	68 (175)	---	71 (94)
Industrial	68 (243)	385 (1,400)	---	---	---
Light	---	---	---	---	110 (186)
Heavy	---	---	---	---	17 (208)
Open Space	---	---	---	---	5 (13)
All Uses	---	---	48 (176)	---	44 (166)

Source: [1] American Public Works Association, "Water Pollution Aspects of Urban Runoff," USEPA Report No. T10060DNS01/69 (WP20 No. 20 070, DNS), January, 1969.

[2] Sartor, J.D., and G.B. Boyd, "Water Pollution Aspects of Street Surface Contaminants," USEPA Report No. EPA-R2-72-081 (WP20 No. 20 [illegible]), November, 1972.

[3] Shelley, P.E., "Identification of Urban Runoff Loads in Three Counties," USEPA Report No. EPA [illegible] (WP20 No. 20 [illegible]), April, 1975.

[4] Telephone communication with Corps of Engineers, 1975.

[5] Sartor, J.D., "Water Quality Considerations in Urban Runoff," USEPA Report No. EPA-600/2-76-274 (WP20 No. 20 [illegible]), August, 1976.

TABLE 22. SAMPLING METHODS FOR MEASURING STREET DUST/DIRT ACCUMULATIONS

Sampling Program	APWA[1]	USGS Research Co.	Shelton&P Inc.	Region 7 Source U.S. Corps of Engineers
Sample Area	Length: Full block frontage from building line parallel to curb Width: Gutter	Length: 19.15 m (62.83 ft) parallel to curb Width: 7.6 m (25 ft) ∆ to curb 74.83 m² (800-1,000 ft²)	Length: 19.81 m (65.100 ft) or more parallel to curb Width: Gutter, 1.2 m (4 ft) ∆ to curb	Length: 1.5 m (5 ft) parallel to curb Width: Gutter, 1.7 m (5.5 ft) ∆ to curb
Land Use	Residential Commercial Industrial	Residential Commercial Industrial	Isolated from land use to the degree possible to reflect "pathway contribution" Some commercial	Primarily Residential
Sampling Techniques	A. Hand Sweeping B. Vacuum Sweeping	A. Hand Sweeping B. Vacuum Sweeping C. Flushing of hand swept area D. Simulated rainfall on unswept street E. Simulated rainfall on swept street	A. Hand Sweeping B. Vacuum Sweeping C. Flushing	A. Hand Sweeping
Sampling Techniques Most Often Employed	A	A on each site C on occasion	A,B,C on each site	A on each each site
Samples Taken	Dry Samples	Dry Samples Liquid Samples	Dry Samples Liquid Samples	Dry Samples
Samples Tested	Dry Samples passing the 6.3 cm (0.16 in) mesh pulverized with subsequent screening by U.S. No. 40 sieve (0.00378 cm (0.0015 in))	Homogenized dry samples and liquid samples composited on the basis of land use	Dry fines remains retained on U.S. No. 8 sieve (0.03 cm (0.012 in)) Liquid samples (Rush Station)	Dry samples passing the U.S. No. 10 sieve (0.02 cm (0.008 in))

Sources: [1] American Public Works Association, "Water Pollution Aspects of Urban Runoff," USEPA Report No. 11020DNS01/69 (NTIS No. PB 214 001), January, 1969.

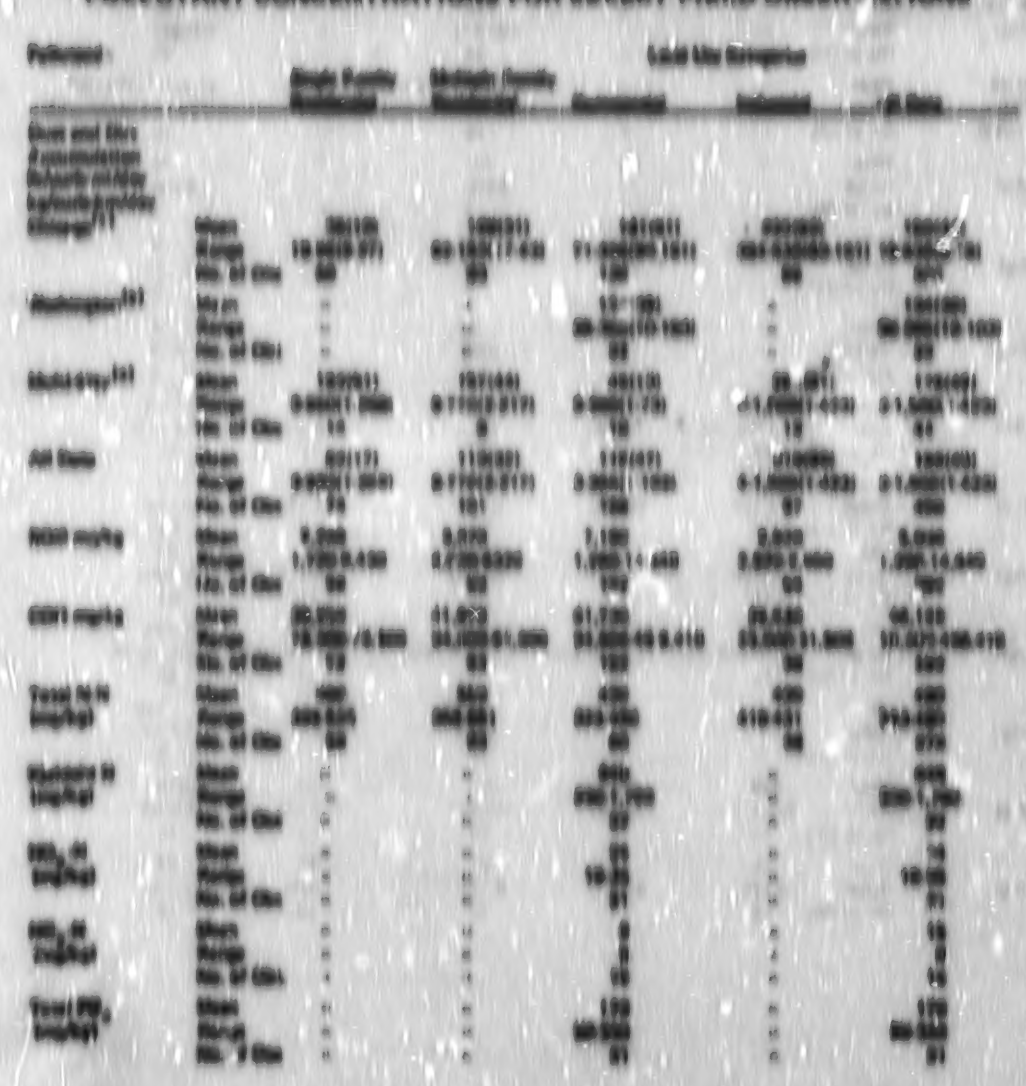
[2] Sartor, J.D. and G.B. Boyd, "Water Pollution Aspects of Street Surface Contaminants," USEPA Report No. EPA-R2-72-081 (NTIS No. PB 214 408), November, 1972.

[3] Shelton, D.R., "Contributions of Urban Roadway Usage to Water Pollution," USEPA Report No. EPA-600/2-76-058 (NTIS No. PB 248 982), April, 1976.

[4] Discussion with U.S. Corps of Engineers survey program was accomplished by telephone conversation with Mr. Jack Hess, the project engineer for the Omaha district in March, 1978.

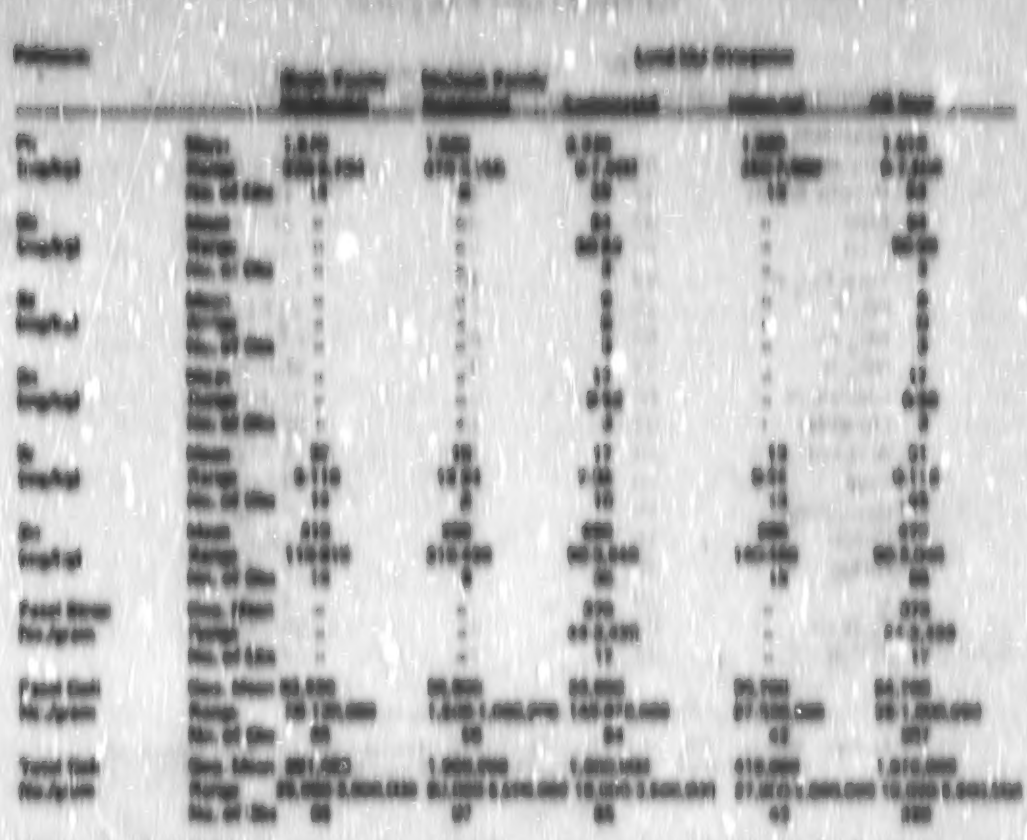
was collected in the Great Lakes area while the greatest data deficiencies existed in the Northwest and Southeast parts of the country. It was concluded that regional comparisons of the data were warranted. A tabulation of the means of all applicable data weighted by the number of samples taken, is shown in Table 10.

TABLE 10. AVERAGE DAILY DUST AND DIRT ACCUMULATION AND RELATED POLLUTANT CONCENTRATIONS FOR SELECT FIELD OBSERVATIONS



[redacted]

TABLE 30 (cont'd)



Sources: [illegible]

Although the foregoing table does not reflect flush samples, the information depicted in Table 31 gives an indication of its significance as a method for capturing additional particulate and soluble materials otherwise unremoved.

TABLE 51. PERCENTAGE OF POLLUTANTS FOUND IN DIRT AND DIRT AND FLUSH SAMPLES ATTRIBUTABLE TO THE FLUSH FRACTION

Pollutant	Number Of Observations	Average Percentage In Flush Fraction	Range Of Flush Fraction Percentages [a]
Accumulation (dry weight)	83	7	0.0-9.6
Volatile Solids	83	20	17.1-22.9
BOD	83	28	21.1-34.6
COD	83	15	13.2-16.7
Total PT_4 [b]	83	13	11.7-14.3
PO_4	83	43	39.7-46.3
NO_3-N	83	69	65.7-74.3
NO_2-N	83	87	85.4-88.6
Kjeldahl N	83	33	27.9-38.1
Chlorides	83	48	36.7-60.0
Asbestos	66	13	9.4-16.6
Lead	10	4	2.0-6.0
Chromium	10	17	8.7-26.3
Copper	10	5	2.0-8.0
Nickel	10	5	2.0-8.0
Zinc	10	2	1.2-2.8
F. Surp	83	44	39.5-48.2
F. Coli	83	76	67.1-84.9

[a] Ranges inferred at 95% confidence interval

Source: Sartor, J.D., "Contributions of Urban Stormwater Loads to Water Pollution," USEPA Report No. EPA-600/2-76-083 (NTIS PB 252 581), April, 1976.

As to deposition characteristics, the majority of street surface solids has been found to accumulate within 6 in. (15 cm) of the curbface and virtually all accumulations may be accounted for within 3.5 ft (1.1 m) of the curb line. Street surface accumulations are not uniformly deposited longitudinally along streets.

When classification of accumulations is based on the U.S. No. 8 sieve, it seems likely that asphaltic concrete wear or weathering products would probably contribute more to the litter fraction while concrete would produce more dust and dirt sized materials. On this basis, about 25 percent or more of the total accumulation on these pavement surfaces may be associated with surfacing materials alone. Accumulation loadings on asphaltic surfaces have been found to be about 80 percent heavier than on concrete streets.

The effects of pavement types, variation in street pattern, curb height and other physical factors can meaningfully influence results. The best use of street accumulation data by itself would appear to be in completely urbanized areas which have fully developed streets and wholly sewered collection systems. In addition, use of this information by itself should be most appropriate for low-intensity runoff events where pervious area contributions are minimal.

STORM and SWMM modeling was applied to some of the street accumulation values developed for five urbanized areas. Exploring the reported pollutant to solids relationships associated with these developed values, and measured annual average pollutant concentrations reported for each, some level of model calibration was possible through the adjustment of dust and dirt values. Dust and dirt correction factors of 1.0 for Atlanta, 0.33 for Denver, 1.33 for Des Moines, 0.1 for Minneapolis, and 0.3 for San Francisco, produced reasonable estimates for single runoff events for the pollutant for which the adjustment was made.

The foregoing discussions have attempted to outline techniques and technologies now available as a basis for estimating the magnitude and significance of urban runoff pollution. In addition, they have attempted to highlight some of the more apparent problems that exist in the use of this information. It is apparent from the foregoing that additional research and investigation are warranted to resolve these problems. Further investigations are needed to better determine temporal time and flow-related variations in discharge pollutant concentrations for urban areas with wholly sewered collection systems. In connection with this effort, street surface accumulation data should be further pursued to clarify the relationships of potential and actual pollutional contributions.

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